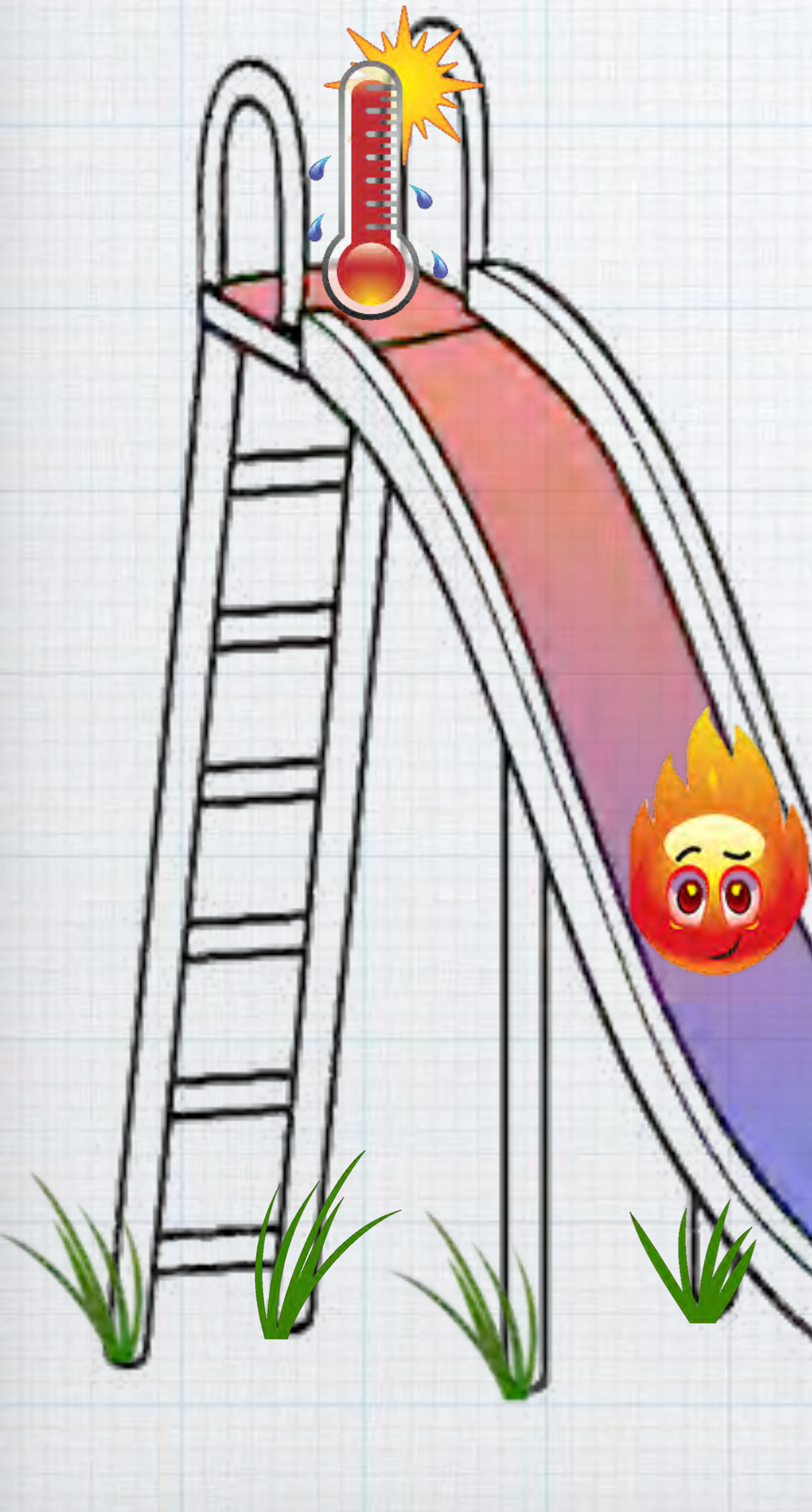
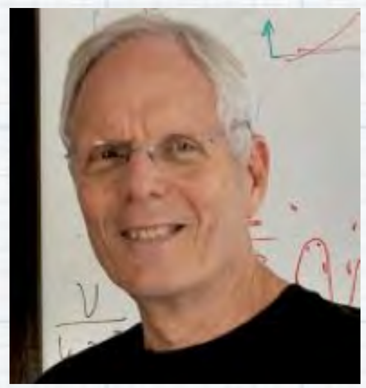
Quantization of Heat Flow in Fractional Quantum Hall States




Moty Heiblum


Amir Rosenblatt


Vladimir Umansky


Yuval Oreg

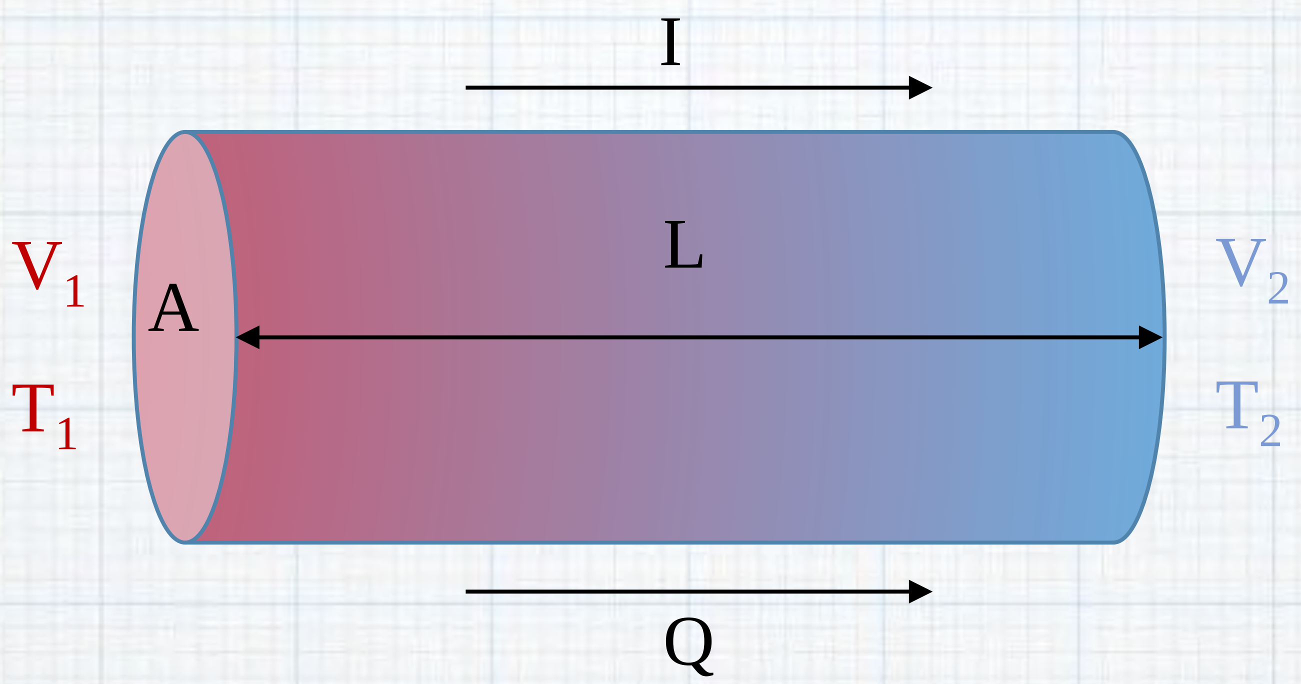

Ady Stern


Dima Feldman

Mitali Banerjee

Braun Center for Submicron Research

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE



$$\sigma = \frac{I}{V_1 - V_2} \cdot \frac{L}{A}$$

$$\kappa = \frac{Q}{T_1 - T_2} \cdot \frac{L}{A}$$

Wiedemann - Franz Law

$$\frac{\kappa}{\sigma} = \frac{\pi^2 k_B^2}{3e^2} T$$

Lorentz No.

heat flow in 1-D ballistic channel

J B Pendry
Quantum limits to the flow of information and entropy
J. Phys. **A:** Math. Gen. **16** (1983) 2161-2171

thermal energy = temperature X entropy

together with energy uncertainty

sets an universal upper limit on energy/heat transfer

universality of quantum (upper) limit of heat flow
per channel for all non-interacting particles

$$KT \leq \kappa_0 T$$

1D ballistic transport

$$\kappa_0 \simeq 9.5\times 10^{-13} W / K^2$$

$$\frac{dJ_{th}}{dT} = \kappa_0 T$$

$$\kappa_0 = \frac{\pi^2 k_B^2}{3h}$$

$$J_{th} = \frac{1}{2}\kappa_0 (T_m^2 - T_0^2)$$

Wiedemann - Franz ballistic 1D channel

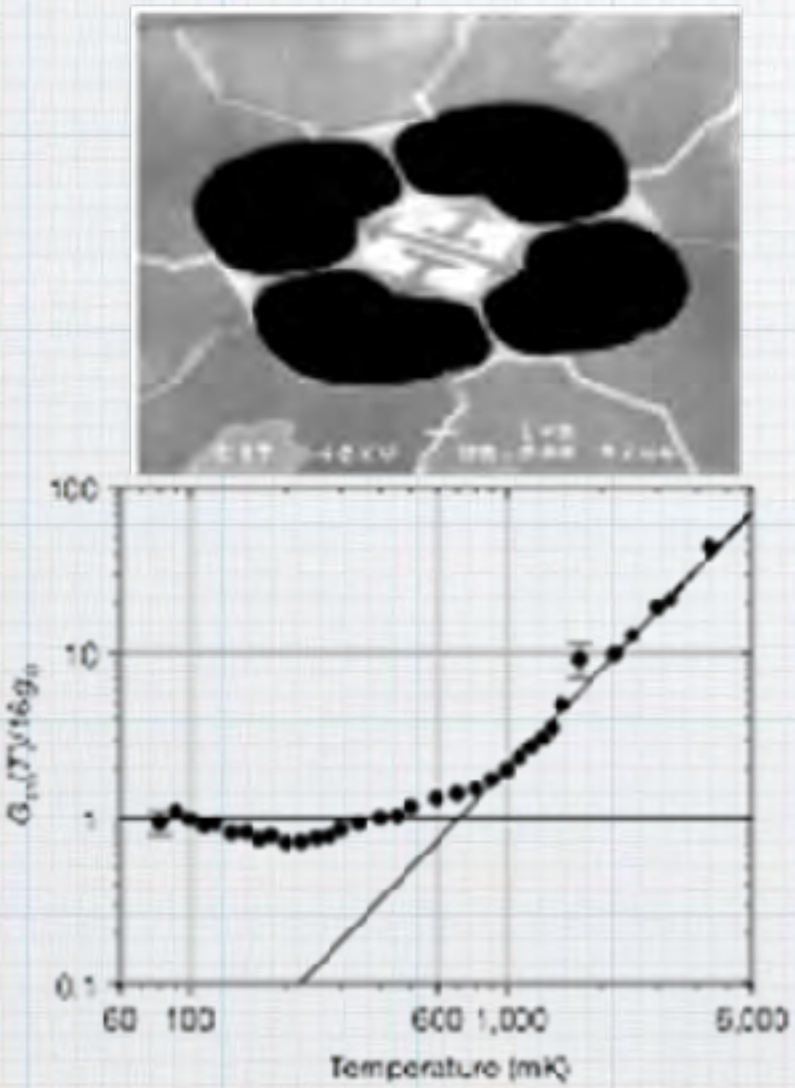
for <u>non-interacting</u> electrons

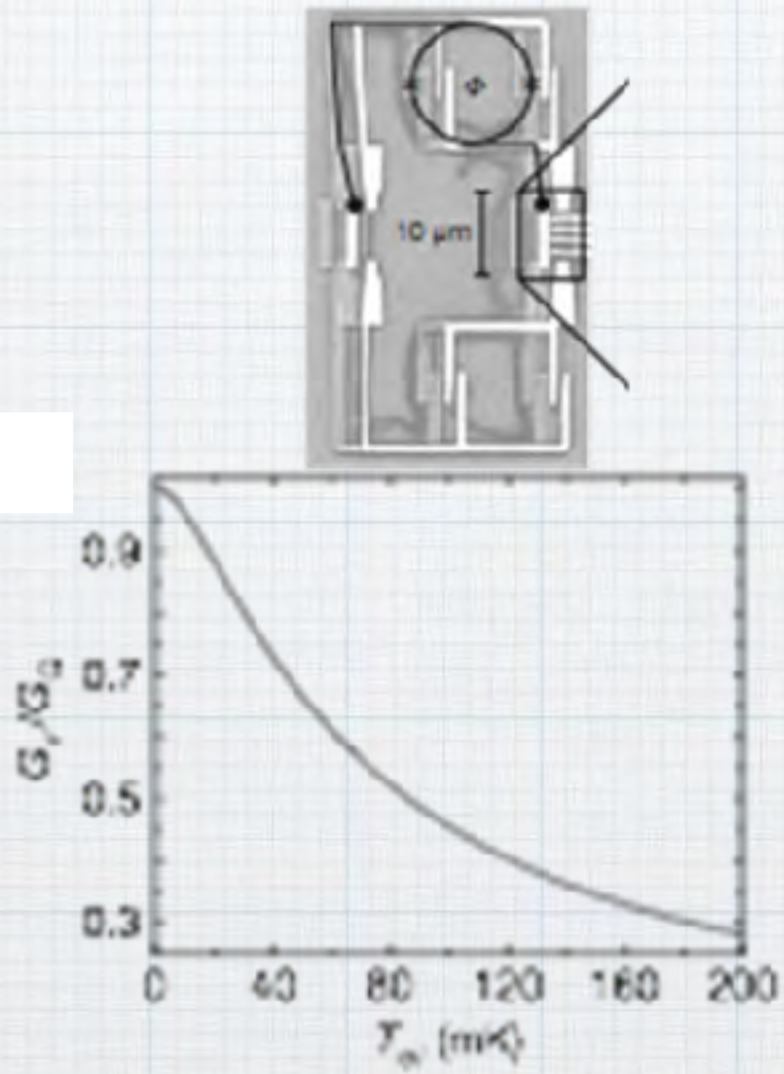
$$G_{th} = \kappa_0 T \qquad G_e = \frac{e^2}{h}$$

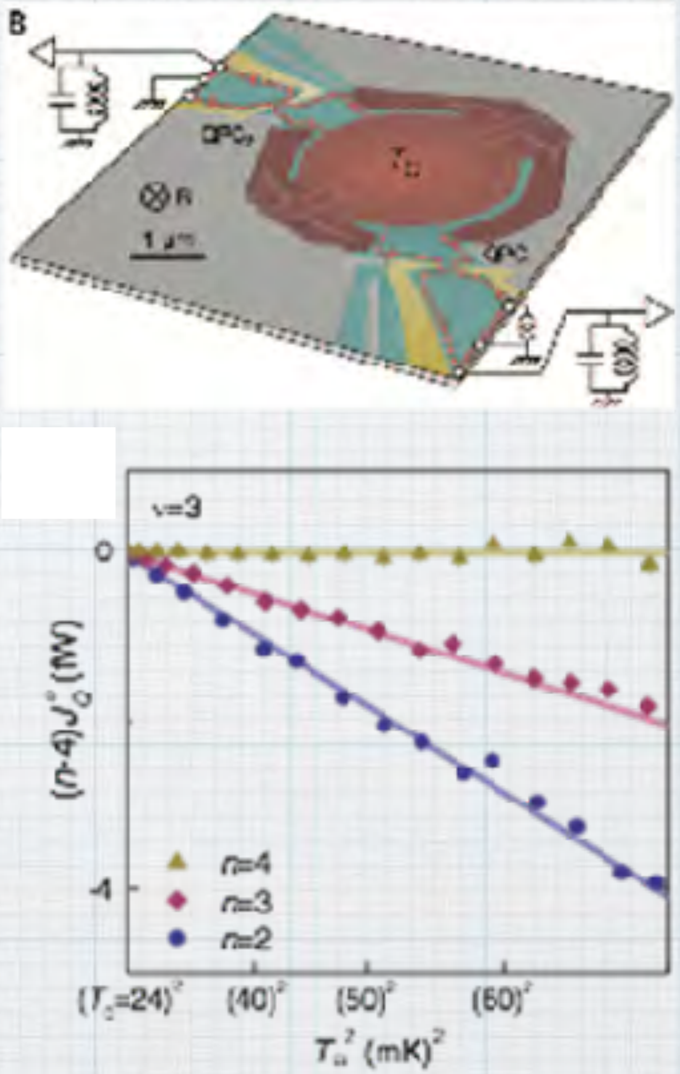
$$\frac{G_{th}}{G_e} = l_{Lorentz} T = \frac{\pi^2 k_B^2}{3e^2} T$$

past experiments…. in accord with theory

16 phonon modes Schwab et al, 2000	single photon mode Meschke et al, 2006	single electron mode Jezouin et al, 2013







Wiedemann – Franz

Non-interacting bosons and fermions both carries the same amount of heat

Interactions....

Pendry's theory extended for **interacting** particles

Kane, C. L. & Fisher, M. P. A.
Quantized thermal transport in the fractional quantum Hall effect
Phys. Rev. B **55,** 15832–15837 (1997)

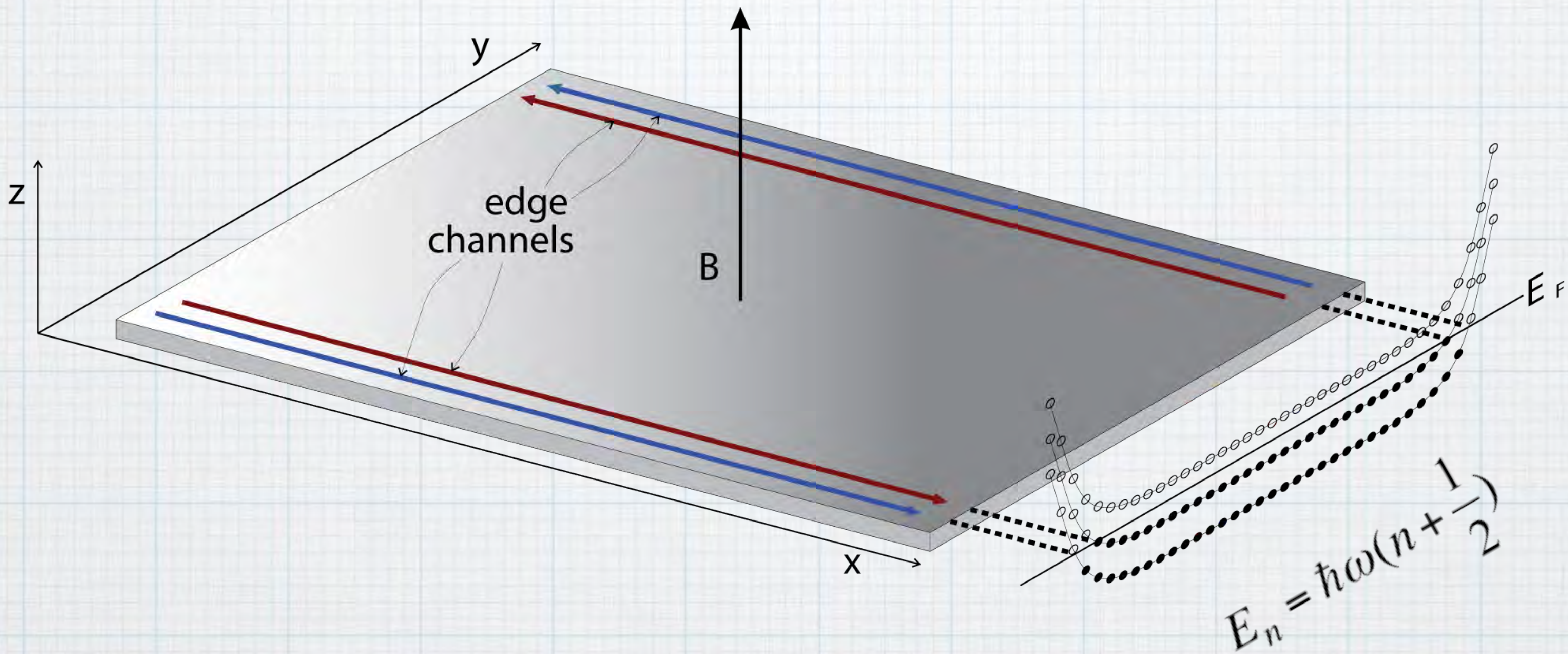
interactions should not effect quantum of thermal conductance !!!

$$K = \kappa_0$$

Wiedemann - Franz law breaks down

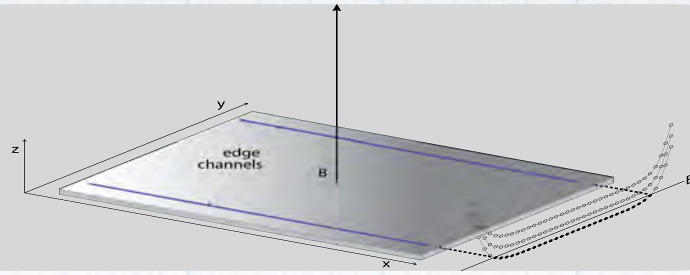
our 1D interacting system......FQHE

Quantum Hall effect : chiral edge modes



each edge mode carries $I = \frac{e^2}{h} V$

1D modes in QHE



bulk of QHE ....insulating localized quasiparticles

edge of IQHE ....integer 1D chiral edge modes $G_H = v\, e^2/h$ $v =$ **1**, **2**, **3**,...

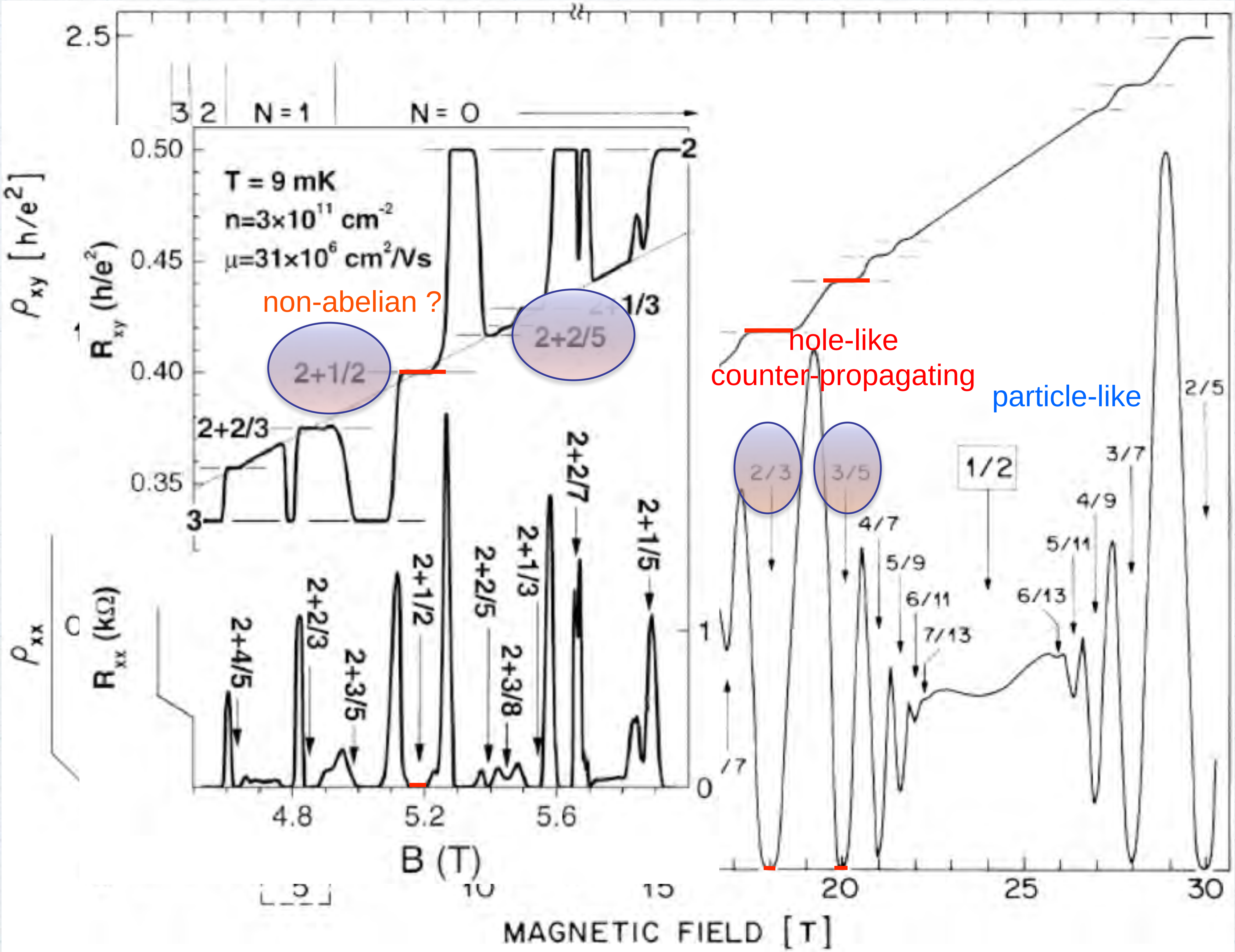
edge of FQHE ....fractional 1D chiral edge modes

abelian states ....$G_H = v\, e^2/h$ $v =$ **1/3**, **2/5**,.., **2/3**, **3/5**, **4/7**,...

non-abelian states (?) ....$G_H = v\, e^2/h$ $v =$ **5/2**, **12/5**,...

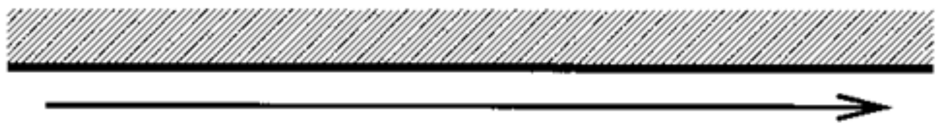
1D modes in FQHE

- *downstream* *charge*...............................particle - like
- *downstream* *charge* + *upstream* *neutral* ...hole – conjugate & non - abelian



T = 9 mK
n=3×10^11 cm^-2
μ=31×10^6 cm^2/Vs
non-abelian ?
2+1/2
2+2/5
1/3
2+2/3
hole-like
counter-propagating
particle-like
2/3
3/5
1/2
4/7
5/9
6/11
7/13
6/13
5/11
4/9
3/7
2/5
2+4/5
2+3/5
2+3/8
2+1/3
2+2/7
2+1/5
N = 1
N = 0
B (T)
MAGNETIC FIELD [T]
ρxy [h/e^2]
Rxy (h/e^2)
ρxx
Rxx (kΩ)

κ in lowest *LL*…*Kane & Fisher* 1997

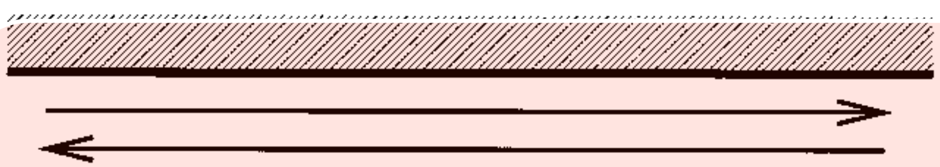


$\nu = 1/3 \to \kappa_0$

1 composite fermion mode

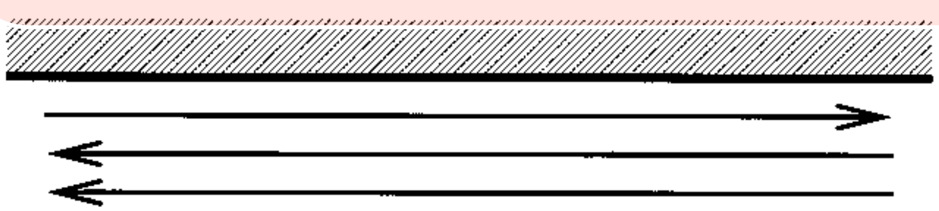
$\nu = 2/5 \to 2\kappa_0$

2 composite fermion modes



$\nu = 2/3 \to 0$

1 charge down - **1** neutral up



$\nu = 3/5 \to -\kappa_0$

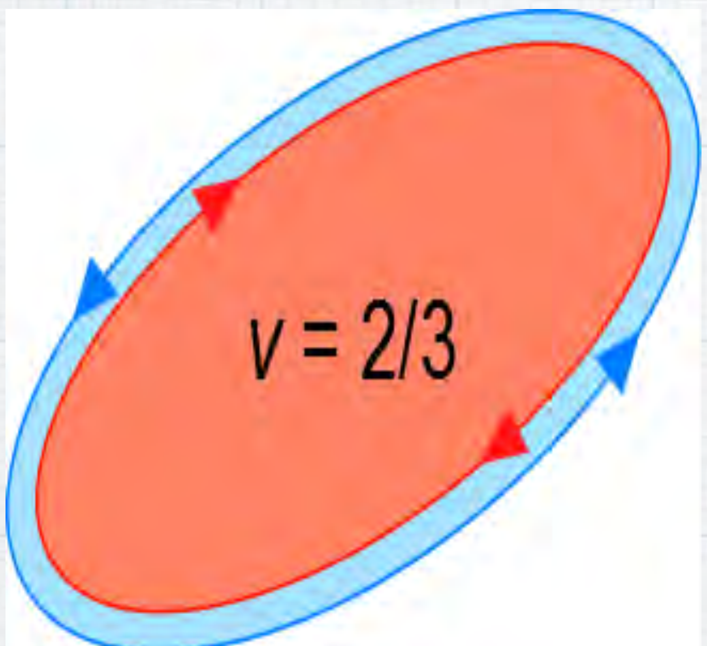
1 charge down - **2** neutral up

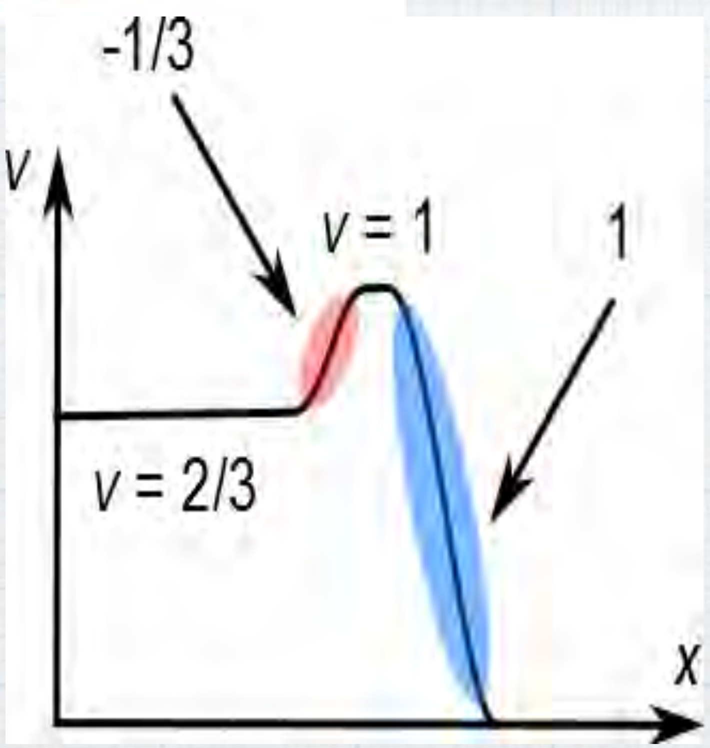
hole - like $\nu = 2/3$ non-equilibrated

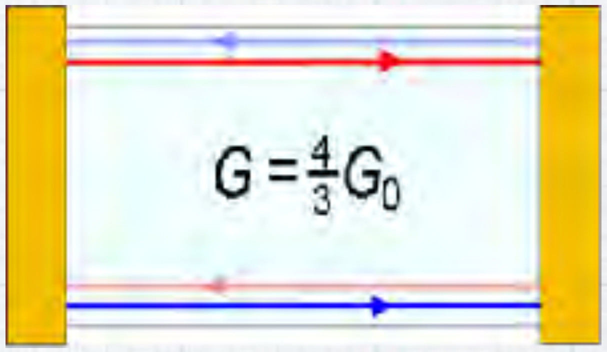
non-equilibrated

$\nu = 2/3 = 1 - 1/3_{\text{upstream}}$

K=0







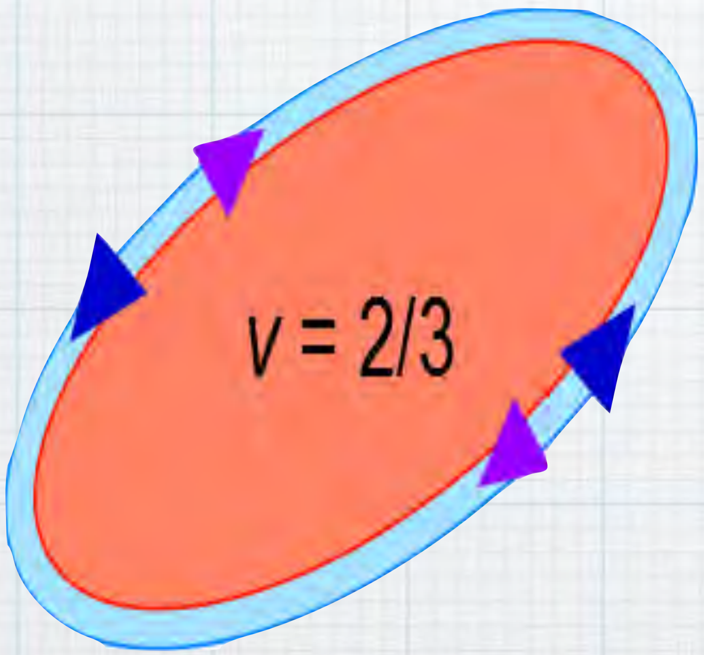
MacDonald, A. H.
Edge states in the fractional quantum Hall effect regime
Phys. Rev. Lett. **64**, 220–223 (1990)

hole - like $\nu = 2/3$ equilibrated

equilibrated

ν = 2/3 = **2/3 – neutral**$_{\text{upstream}}$

K=0



Kane, C. L., Fisher, M. P. A. & Polchinski, J.
Randomness at the edge:
theory of quantum Hall transport at filling 2/3
Phys. Rev. Lett. **72**, 4129–4132 (1994)

neutral modes....carrying energy w/o net charge equilibration of **counter-propagating** charge modes

⇩

topological **neutral modes**

* invisible in conductance measurements

* bosonic thermal conductance κ_0

* associated only with particular FQHE states

Why thermal conductance in FQHE?

* **topological constant** : determined by bulk wave-function
  * reveals **NET** chirality of modes (down-up)
* insensitive to edge reconstruction

these are true for abelian particles

however ....

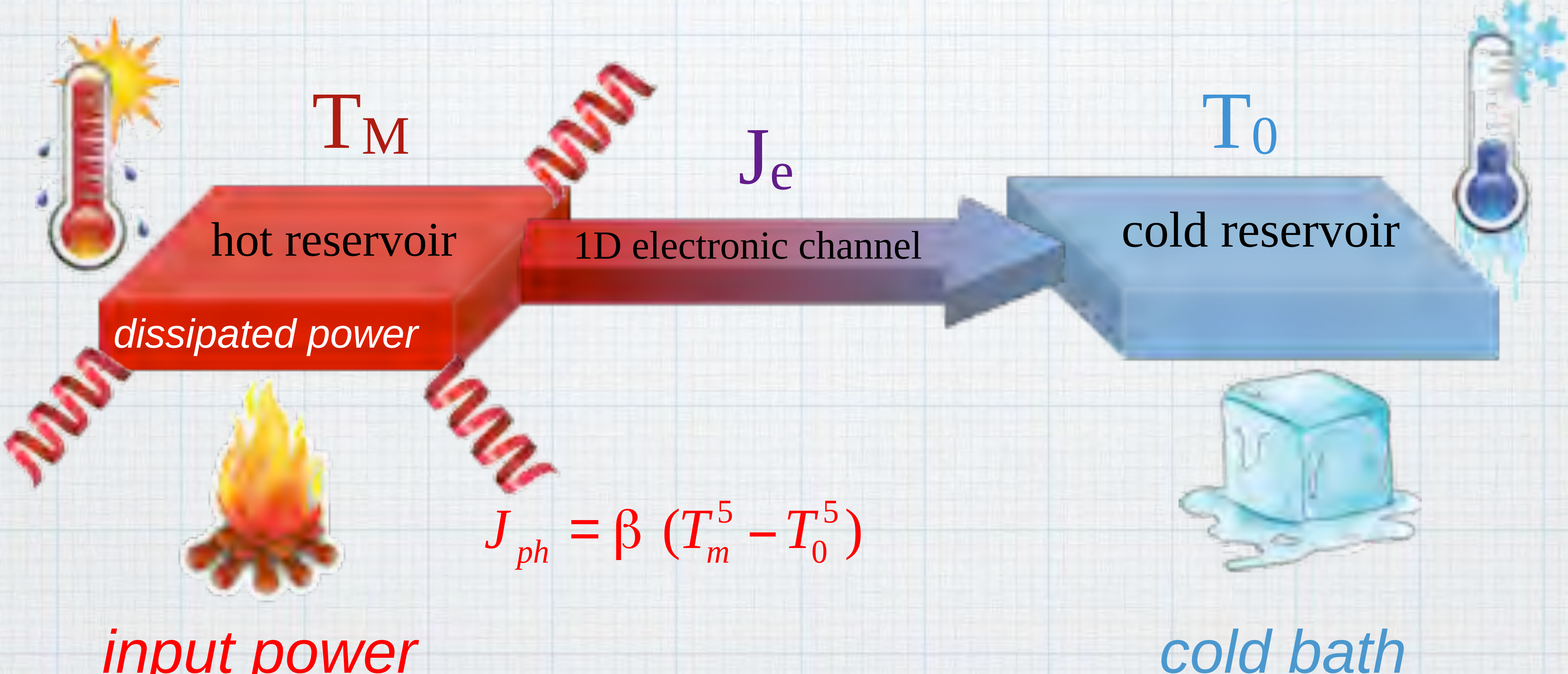
$$K_{non-abelian} = (n + \frac{1}{2})\kappa_0$$ **(Majorana)**

The experiment

Working principle :

flow of dissipated power…..

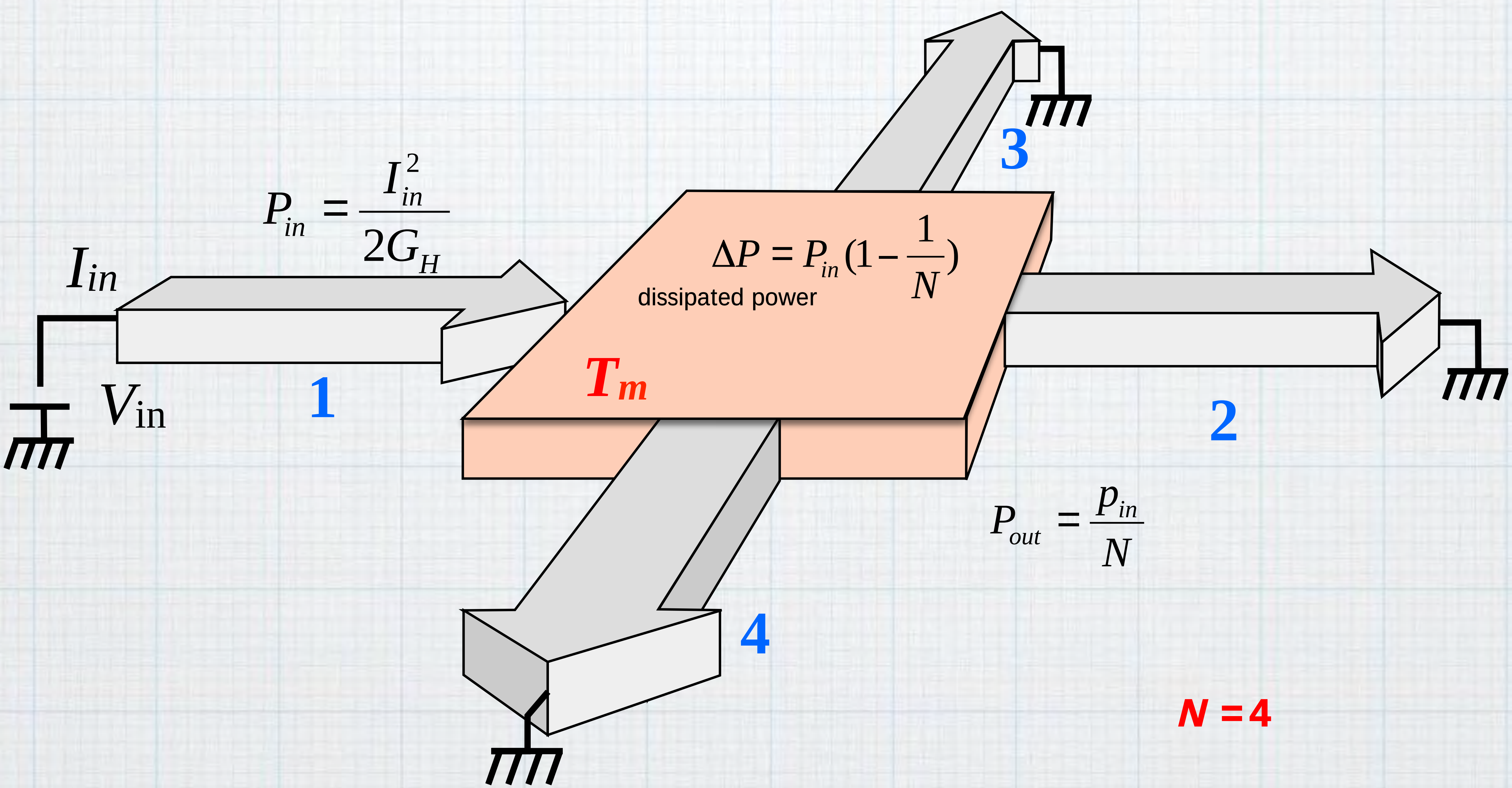
$$J_{tot} = \underbrace{\frac{1}{2}\kappa_0 (T_m^2 - T_0^2)}_{\text{electrons}} + \underbrace{J_{ph}}_{\text{phonons}}$$



$$J_{ph} = \beta\, (T_m^5 - T_0^5)$$

Wellstood, F. C., Urbina, C. & Clarke, J.
Hot-electron effects in metals.
Phys. Rev. B **49**, 5942–5955 (1994)

N - arm device



$P_{in} = \frac{I_{in}^2}{2G_H}$
I_{in}
V_{in}
1
2
3
4
$\Delta P = P_{in}(1 - \frac{1}{N})$
dissipated power
T_m
$P_{out} = \frac{p_{in}}{N}$
$N = 4$

we measure **only temperature**…

electron temperature in grounded contacts…..T_0

electron temperature in heated reservoir…….T_m

$$\Delta P = J_{th}^{total} = 0.5\,K\,(T_m^2 - T_0^2) + \beta\,(T_m^5 - T_0^5)$$

- small ***T***..........phonon term irrelevant
- high ***T***...........phonon term subtracted

- ***K*** determined

measuring temperature

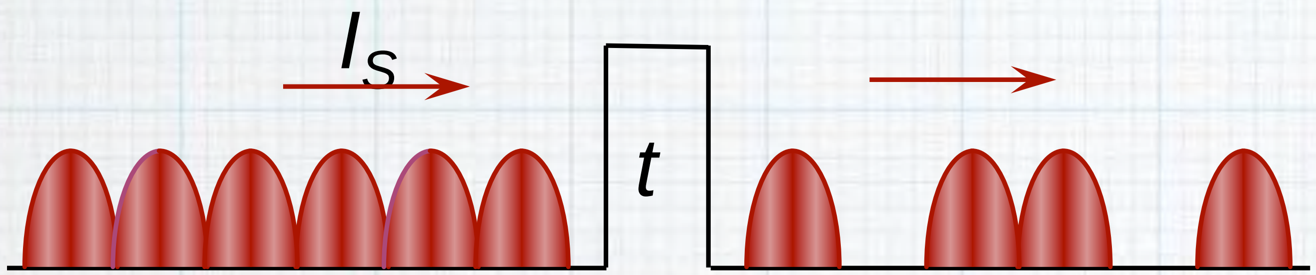
temperature in grounded contacts.....T_0

shot noise

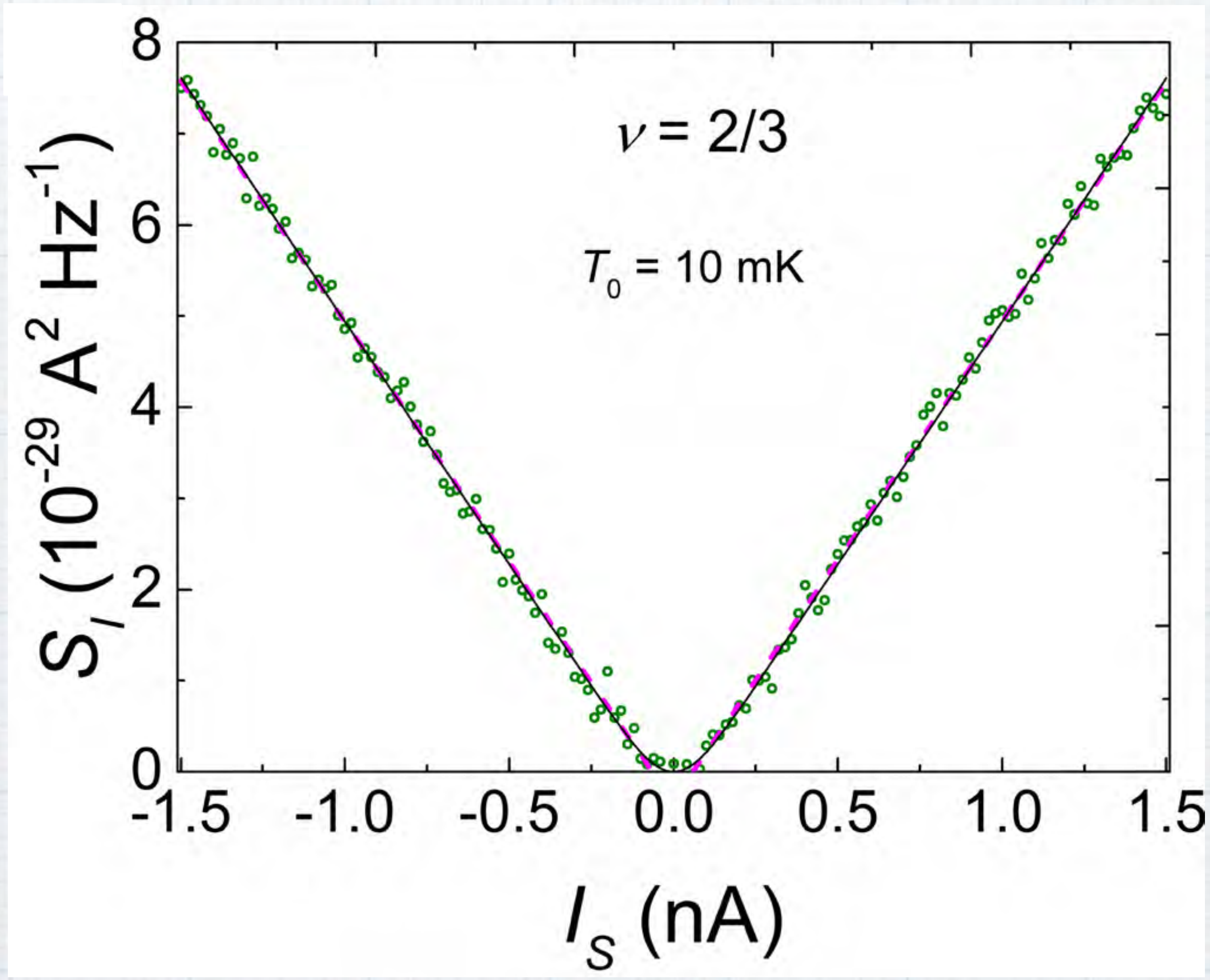
excess temperature in heated reservoir.......$T_m - T_0$

thermal noise

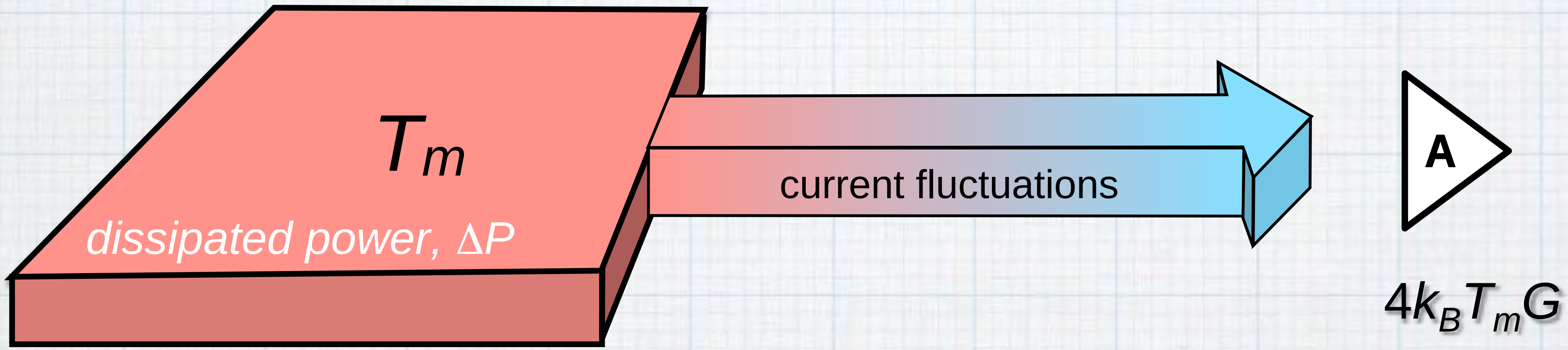
measuring T_0 ……*shot noise*



$$S_i(\omega :\ 0) = 2e^* I_S t(1-t)\cdot \Im(V_S, T) + 4k_B T G$$



measuring T_m ……*Johnson-Nyquist noise*

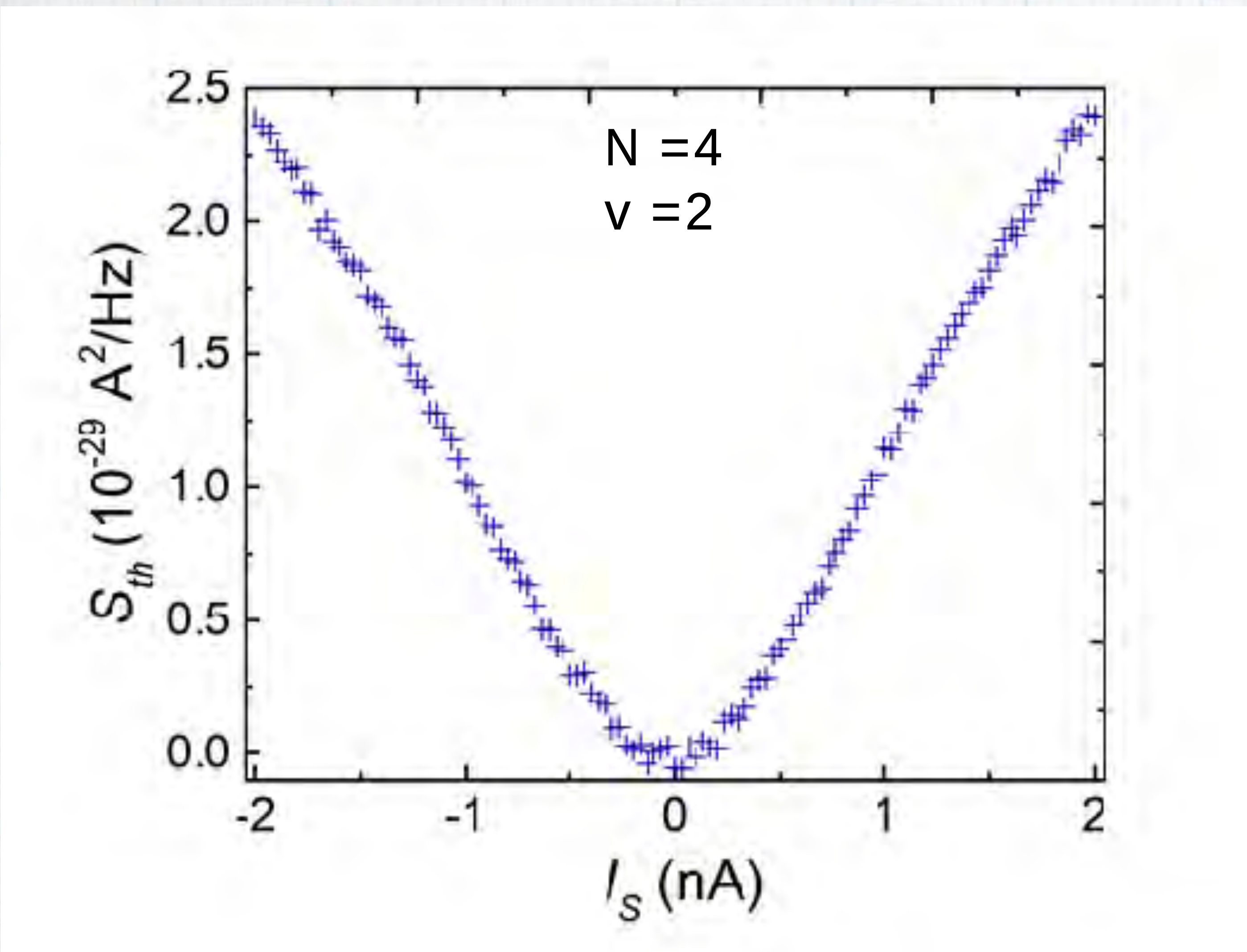


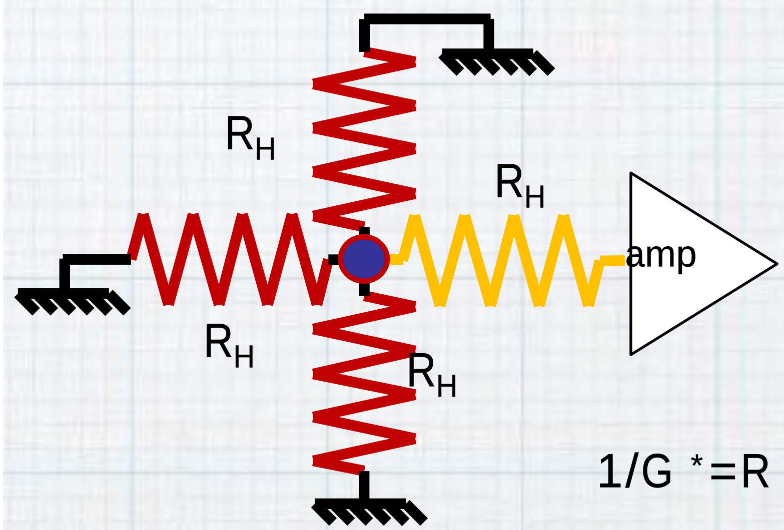
- modes leave contact with noise $4k_BT_mG$
- even if modes cool down with distance...

low frequency current fluctuations conserved

measuring T_m ……*Johnson-Nyquist noise*

excess Johnson - Nyquist noise … $2k_B G^*(T_m - T_0)$

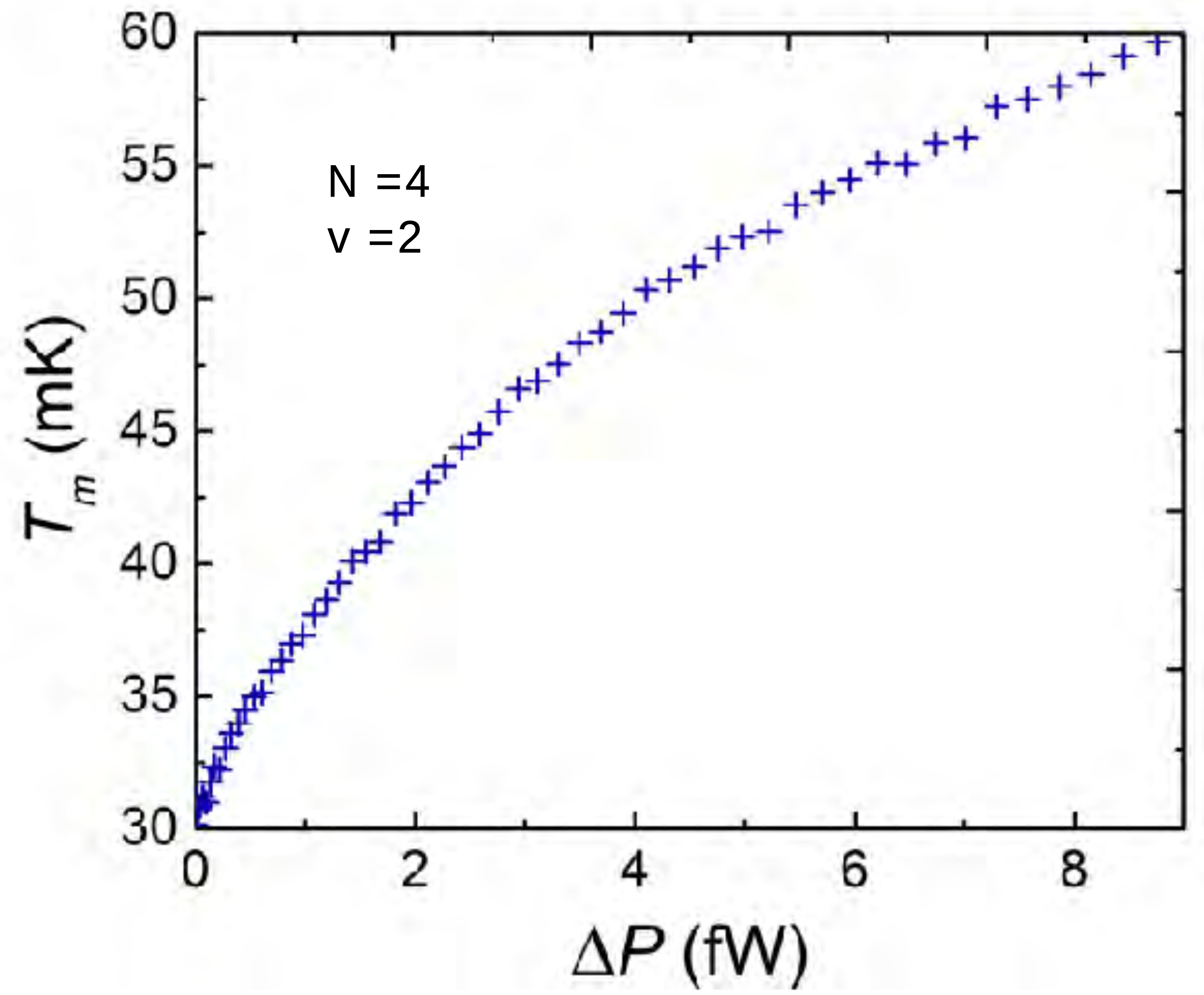




N =4

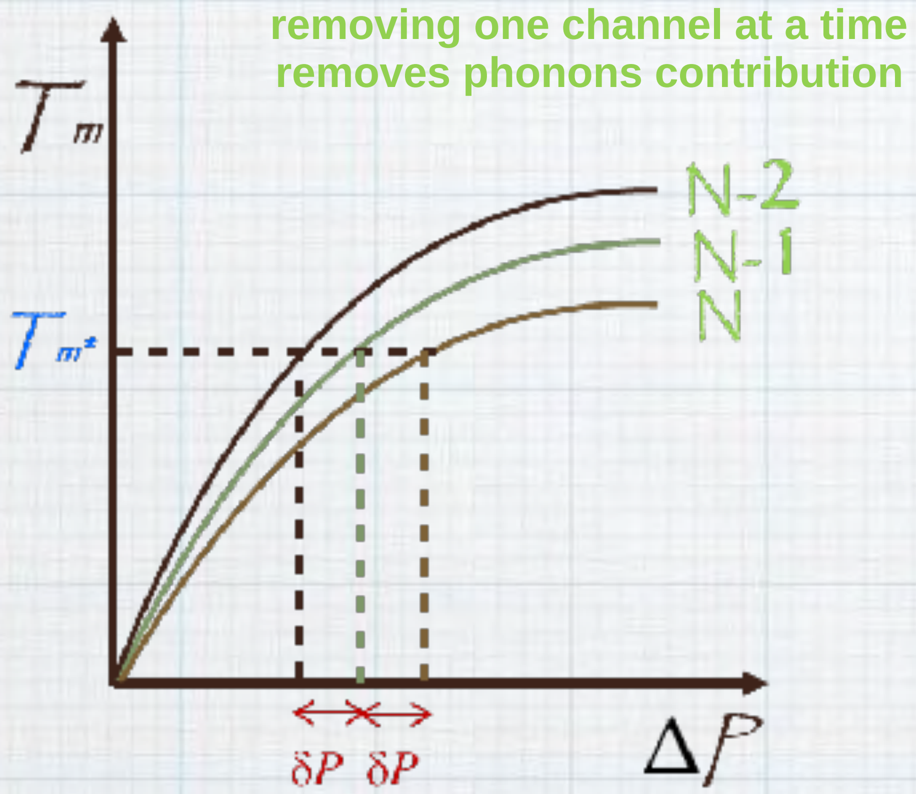
$1/G^* = R^* = R_H + R_H/3$

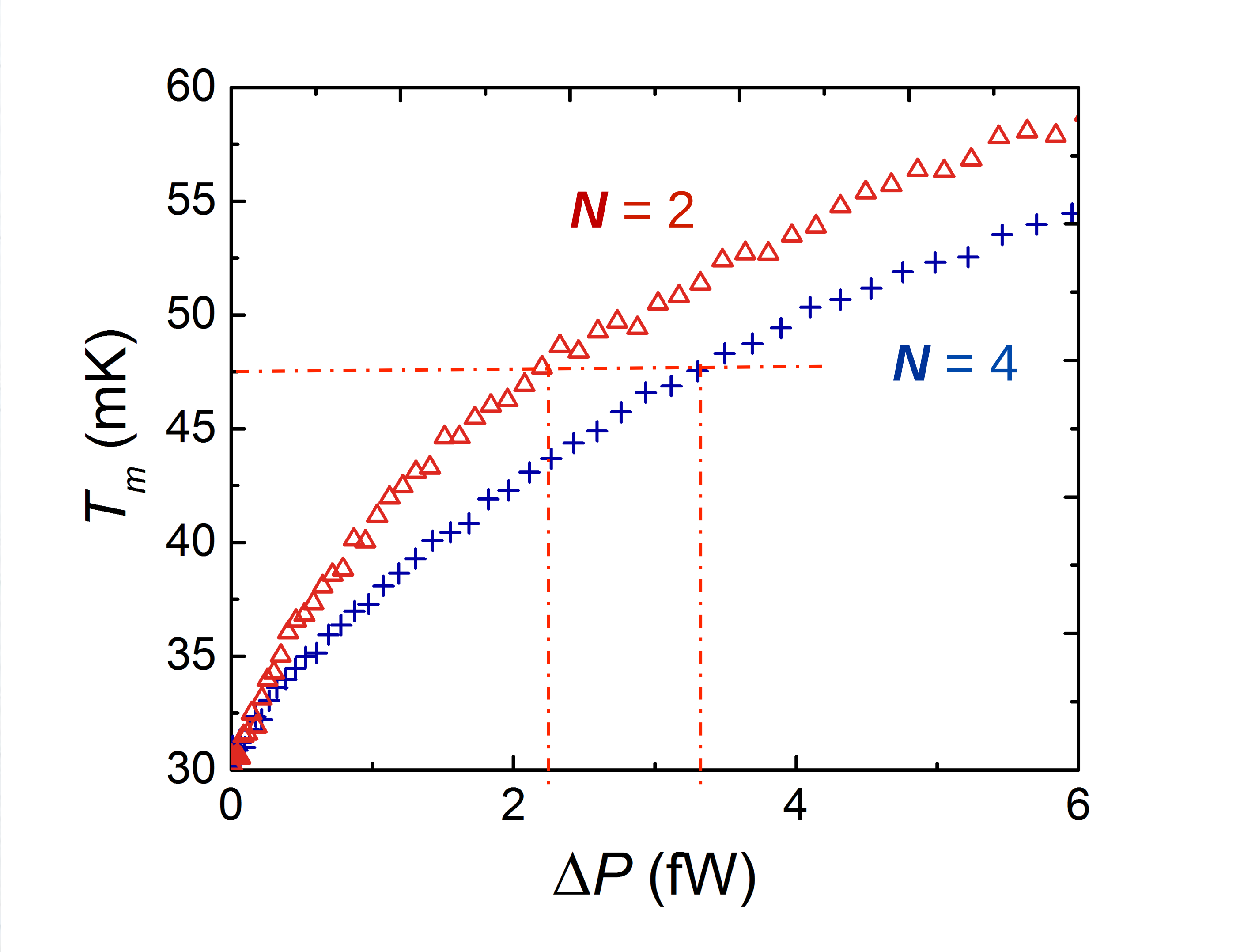
T_m vs dissipated power



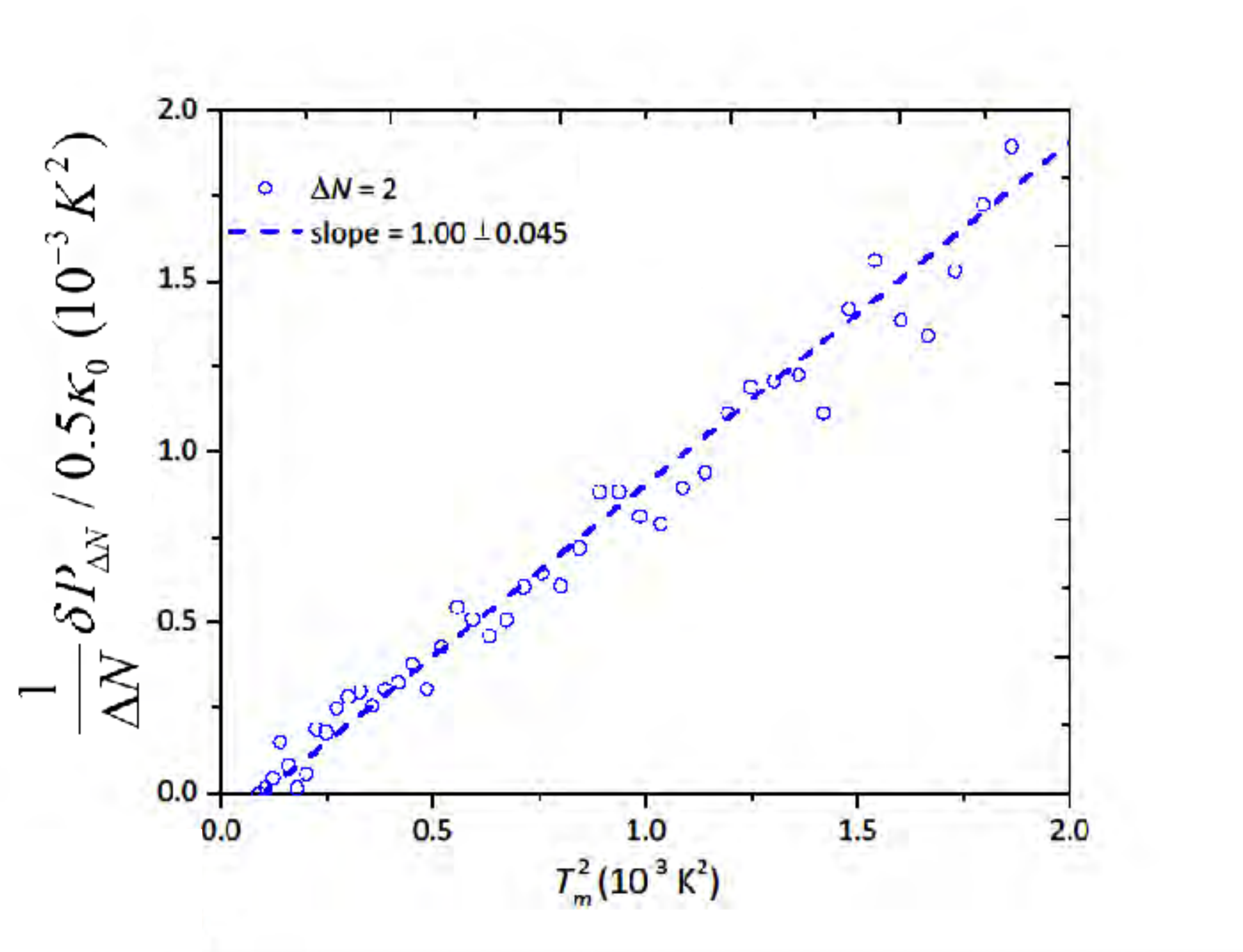
actual analysis

$$J_{tot} = \frac{1}{2}\kappa_0(T_m^2 - T_0^2) + J_{ph}$$

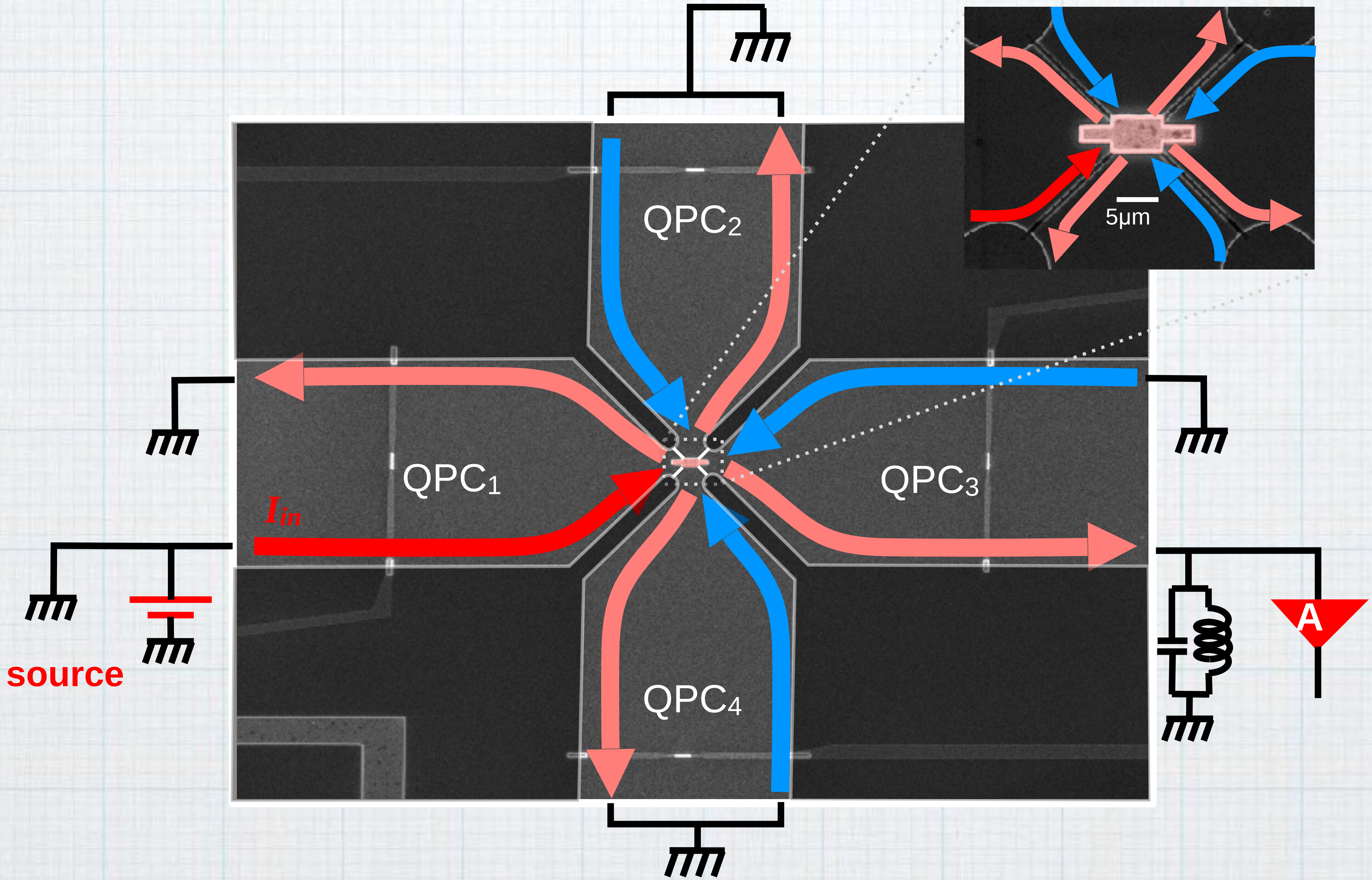




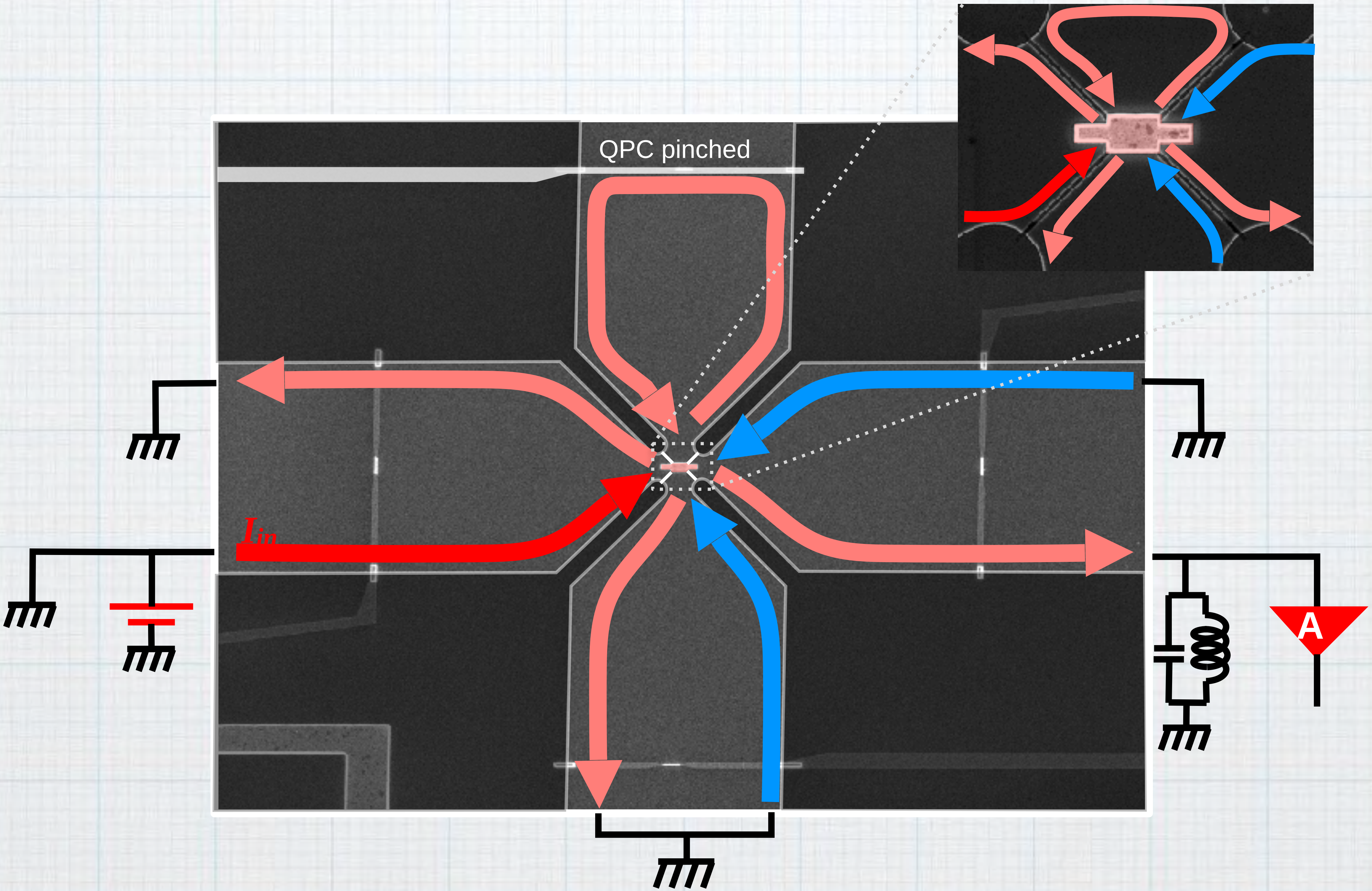
getting κ



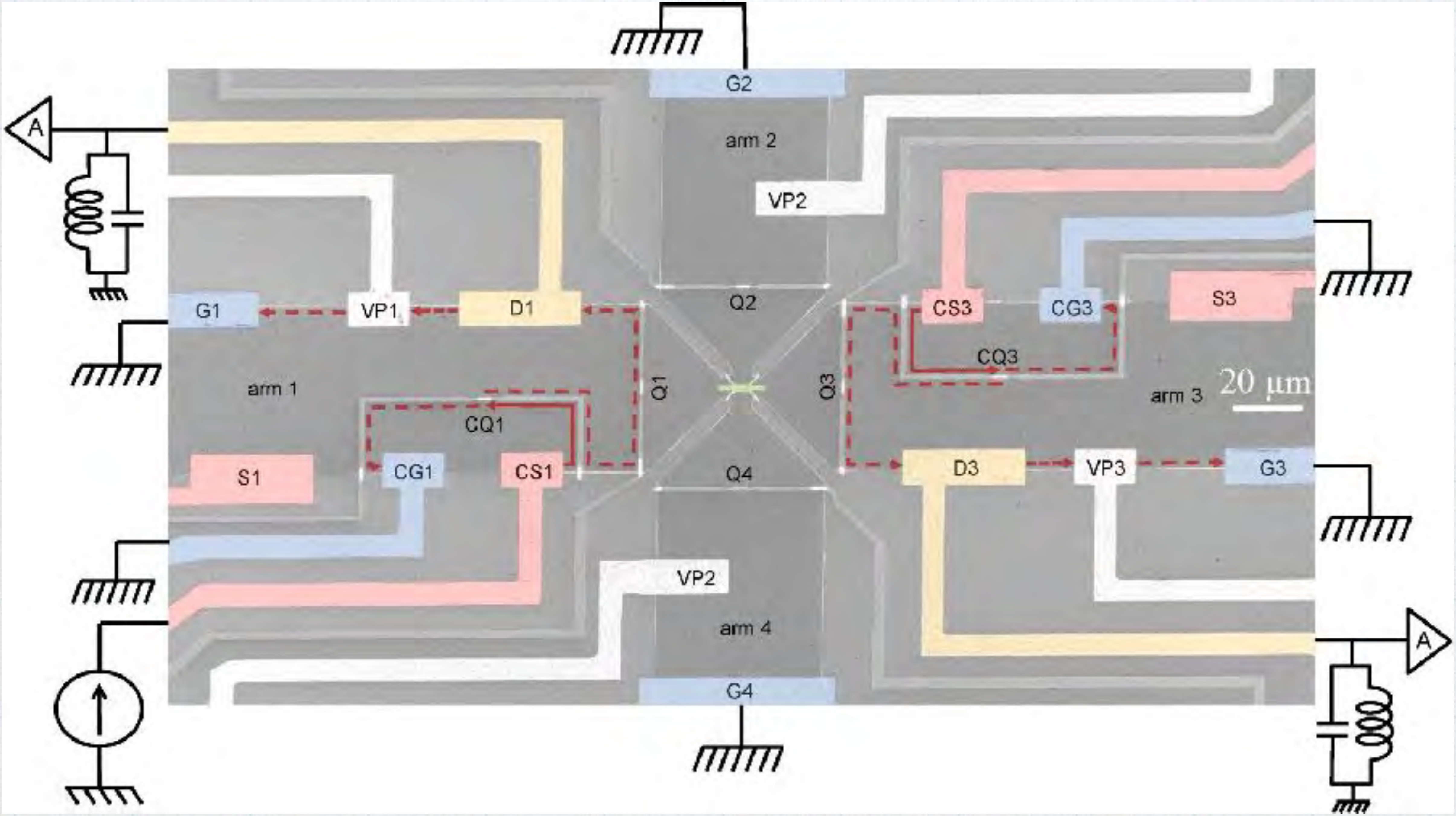
realization.......N = 4



N = 3



realized structure



points of consideration *not an easy experiment*

- electrons fully equilibrate in the small floating reservoir T_m

- outgoing charge channels carry **only** Johnson-Nyquist noise

  without shot noise

- no presence of bulk energy modes (may increase the *apparent* thermal conductance)

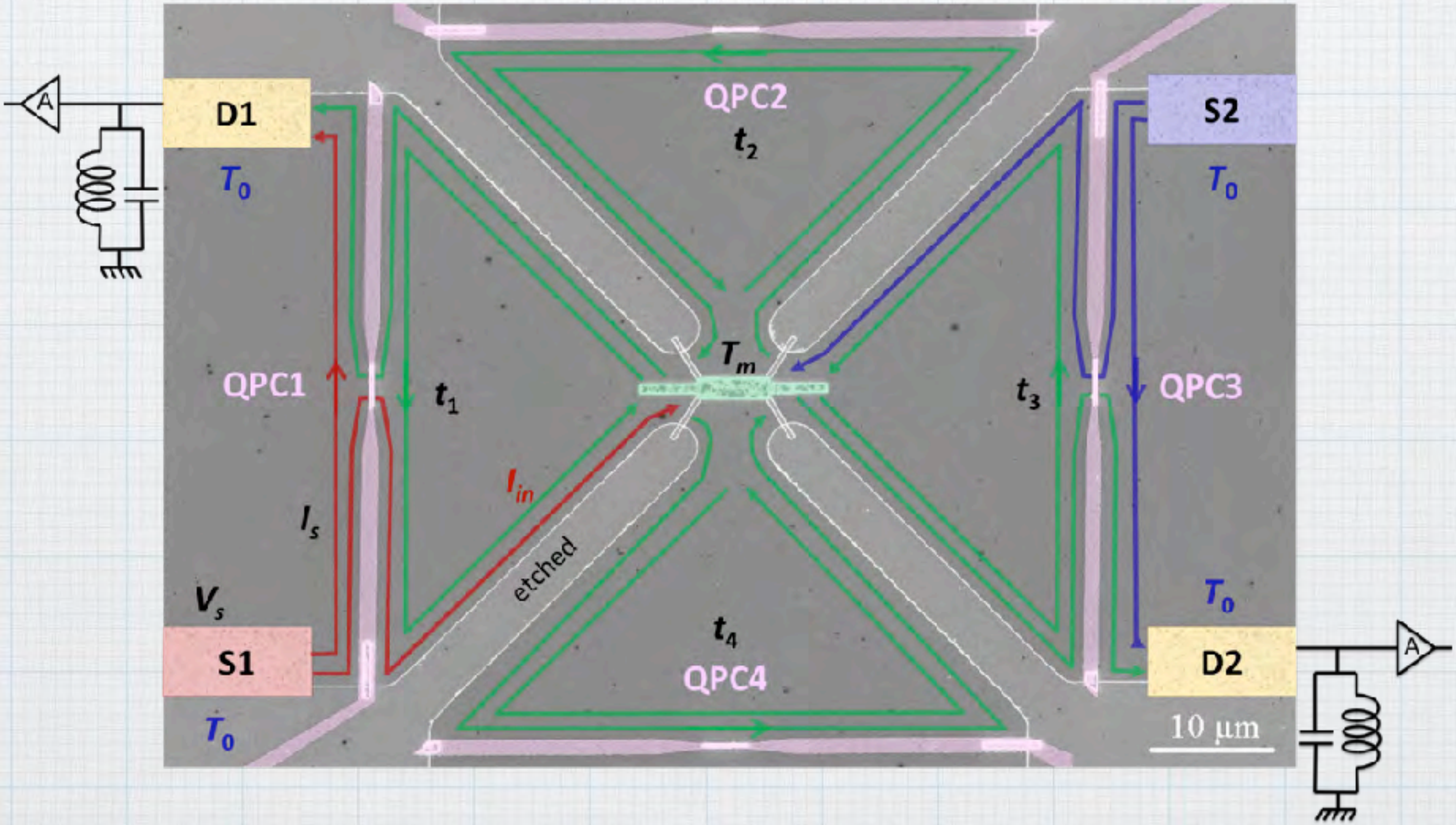
- length of arms is limited (~150μm, temperature equilibration between up-down modes)

- equal splitting between arms, amplifier gain determination, contacts' resistance, ...

* weak interaction regime (IQHE) $\nu = 2, 1$
* strong interaction regime (FQHE)
  * particle - like : $\nu = \frac{1}{3}$
    * hole - like : $\nu = \frac{2}{3}, \frac{3}{5}, \frac{4}{7}$

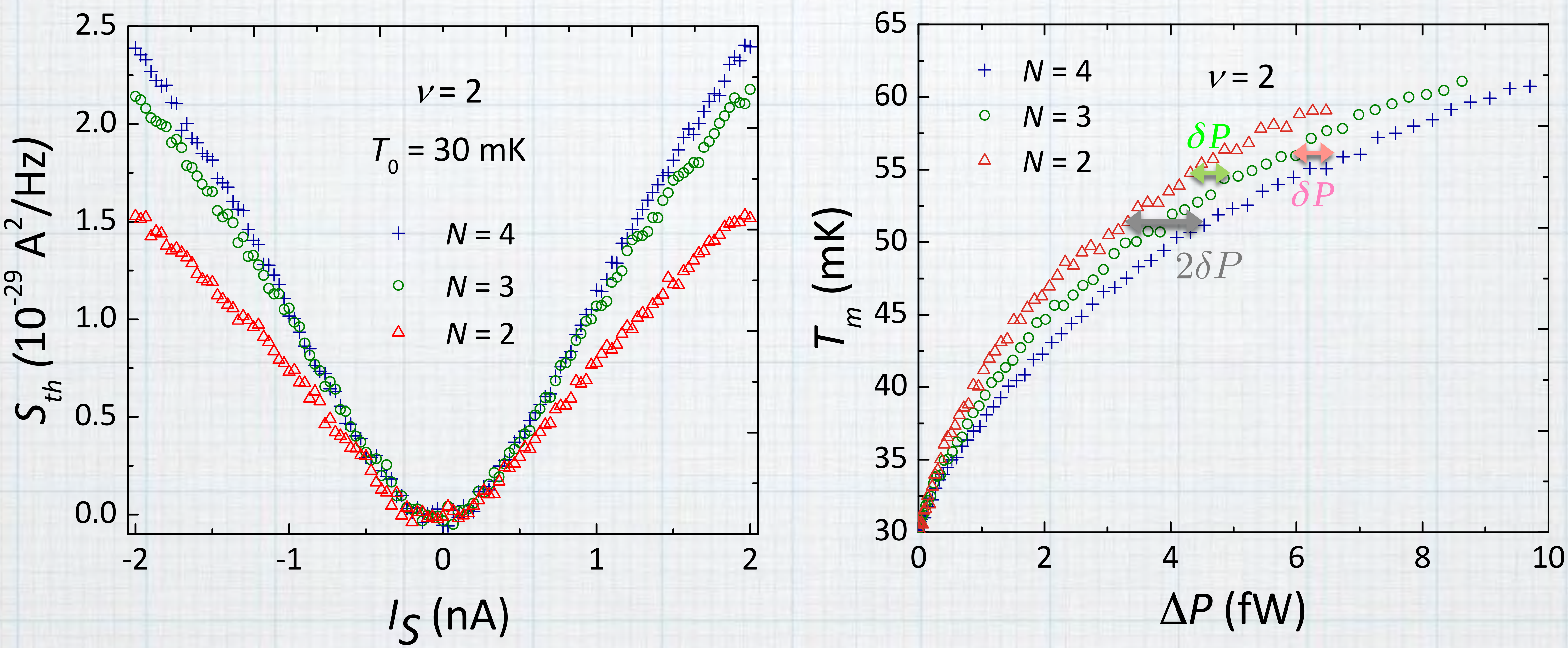
$\nu = 2 \quad \nu_{QPC} = 1$

$N = 2$



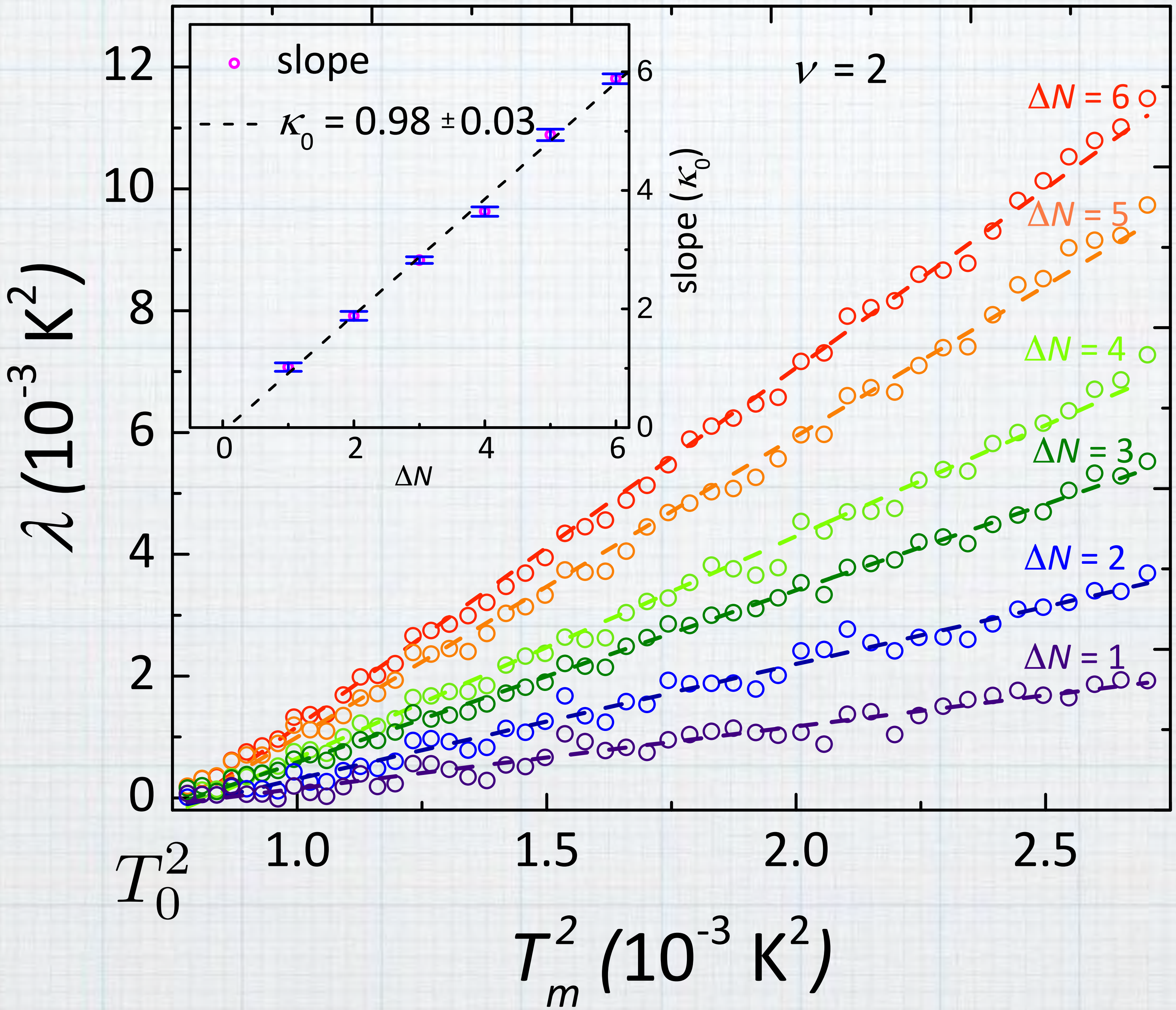
Results :

$$\nu = 2$$



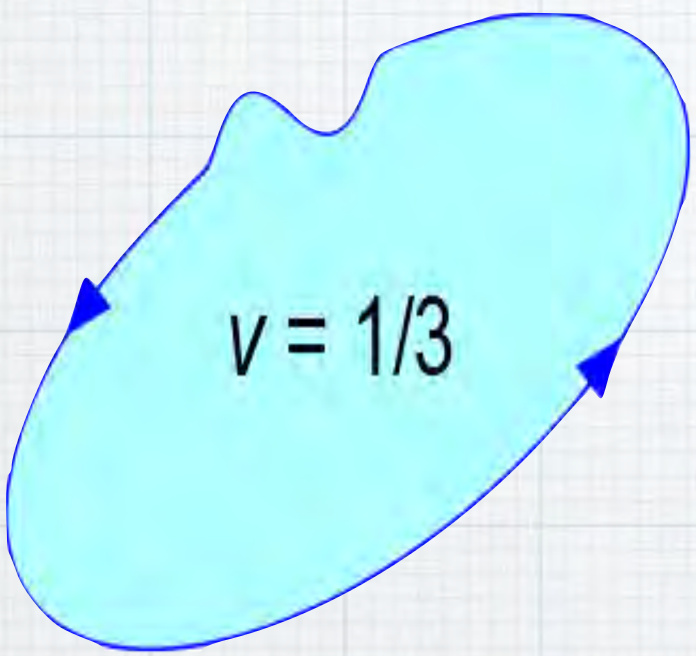
Results :

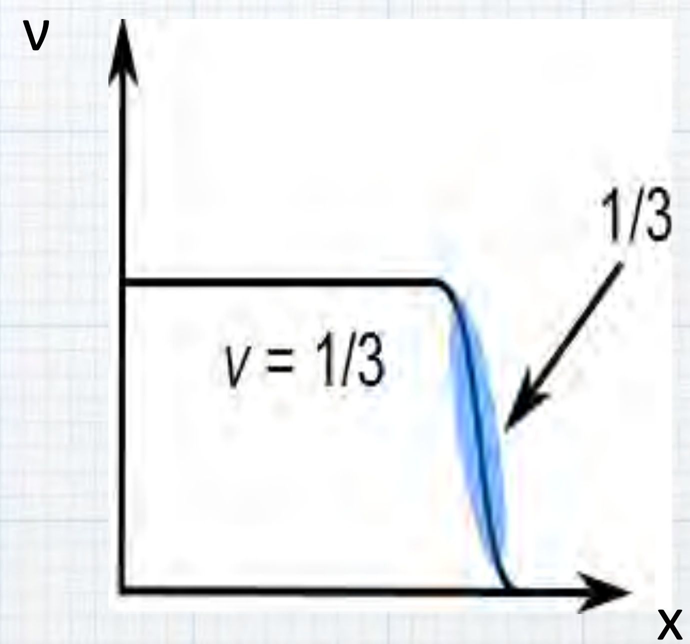
$$\nu = 2$$



$$\lambda = \Delta P/\kappa$$

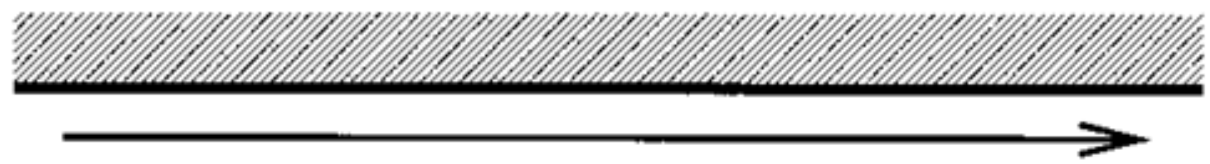
particle - like ν = 1/3





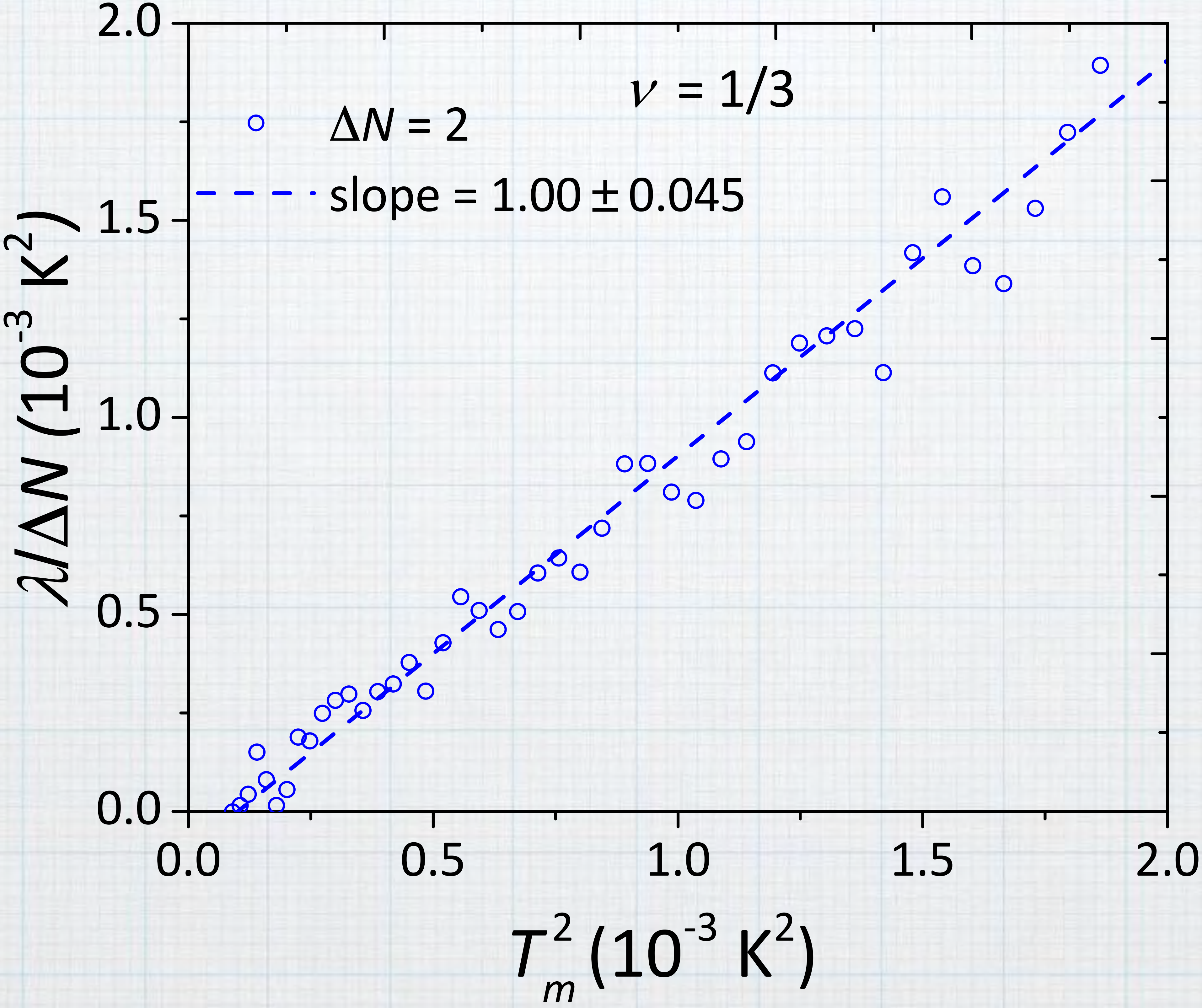
bulk: gapped - incompressible liquid

edge: single charge mode $G=G_0/3$ $K = \kappa_0$



$\nu = 1....1/3 \rightarrow \kappa_0$

1 electron mode....**1** composite fermion mode



ν = 1/3
ΔN = 2
slope = 1.00 ± 0.045
λ/ΔN (10^-3 K^2)
T_m^2 (10^-3 K^2)
0.0
0.5
1.0
1.5
2.0

interactions do not affect ***K***

what about ***K*** of neutral modes ?

more complex fractions…

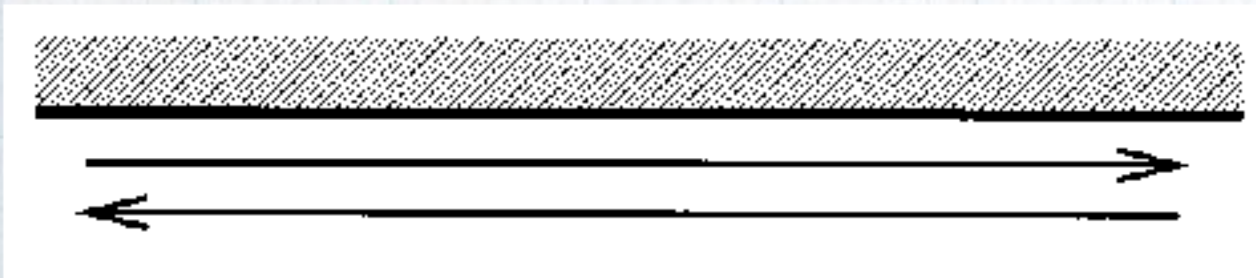
fractional hole-conjugate states……$1/2 < \nu < 1$

full Landau level with holes
hence, counter-propagating modes

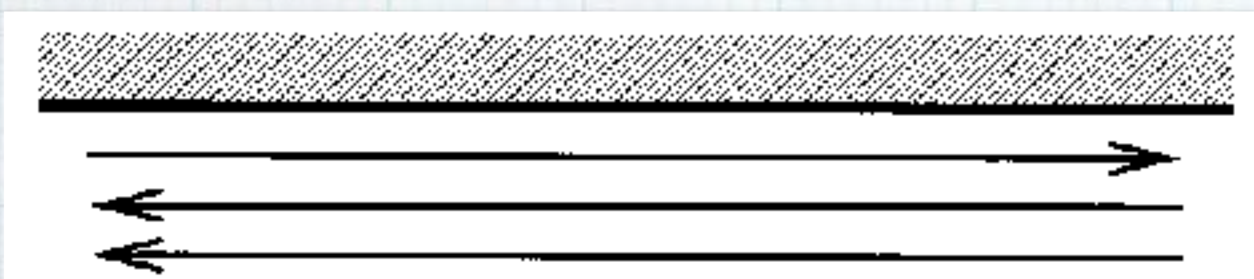
always with upstream *neutral* modes

ν = 2/3, 3/5, 4/7

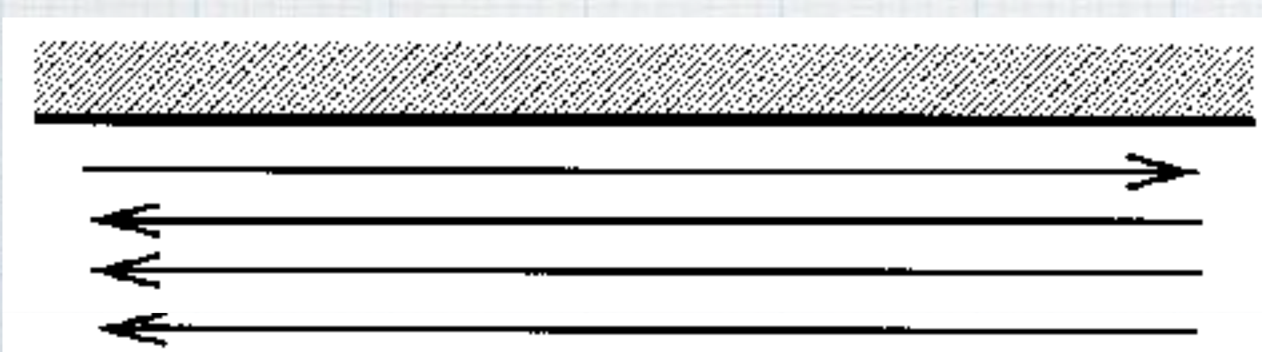
K of hole - states…*Kane & Fisher* 1997



$\nu = 2/3 \rightarrow K = 0$ **1** charge down - **1** ***neutral*** up

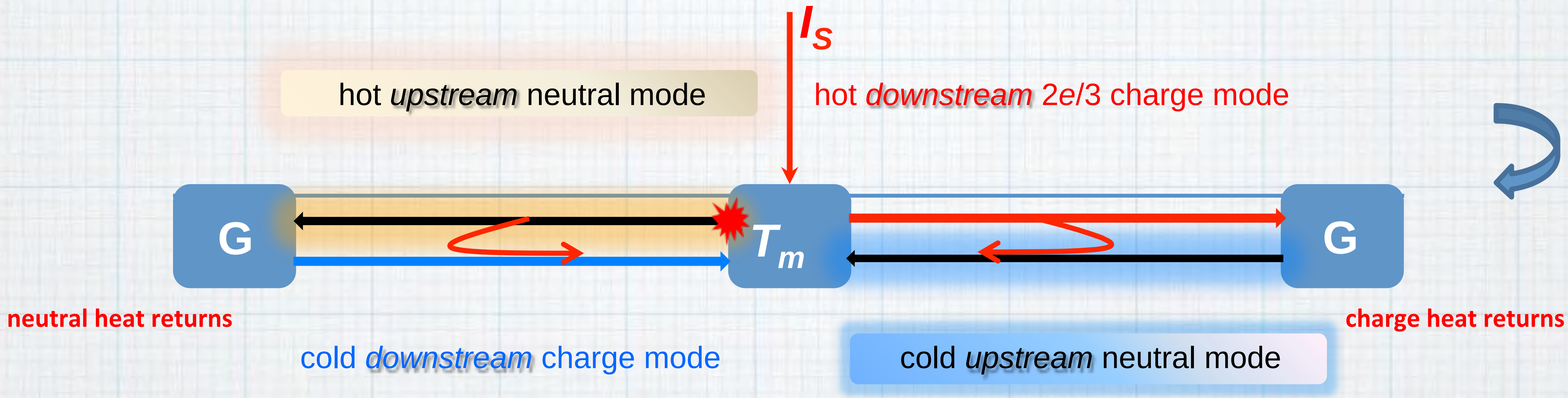


$\nu = 3/5 \rightarrow -\kappa_0$ **1** charge down - **2** ***neutral*** up



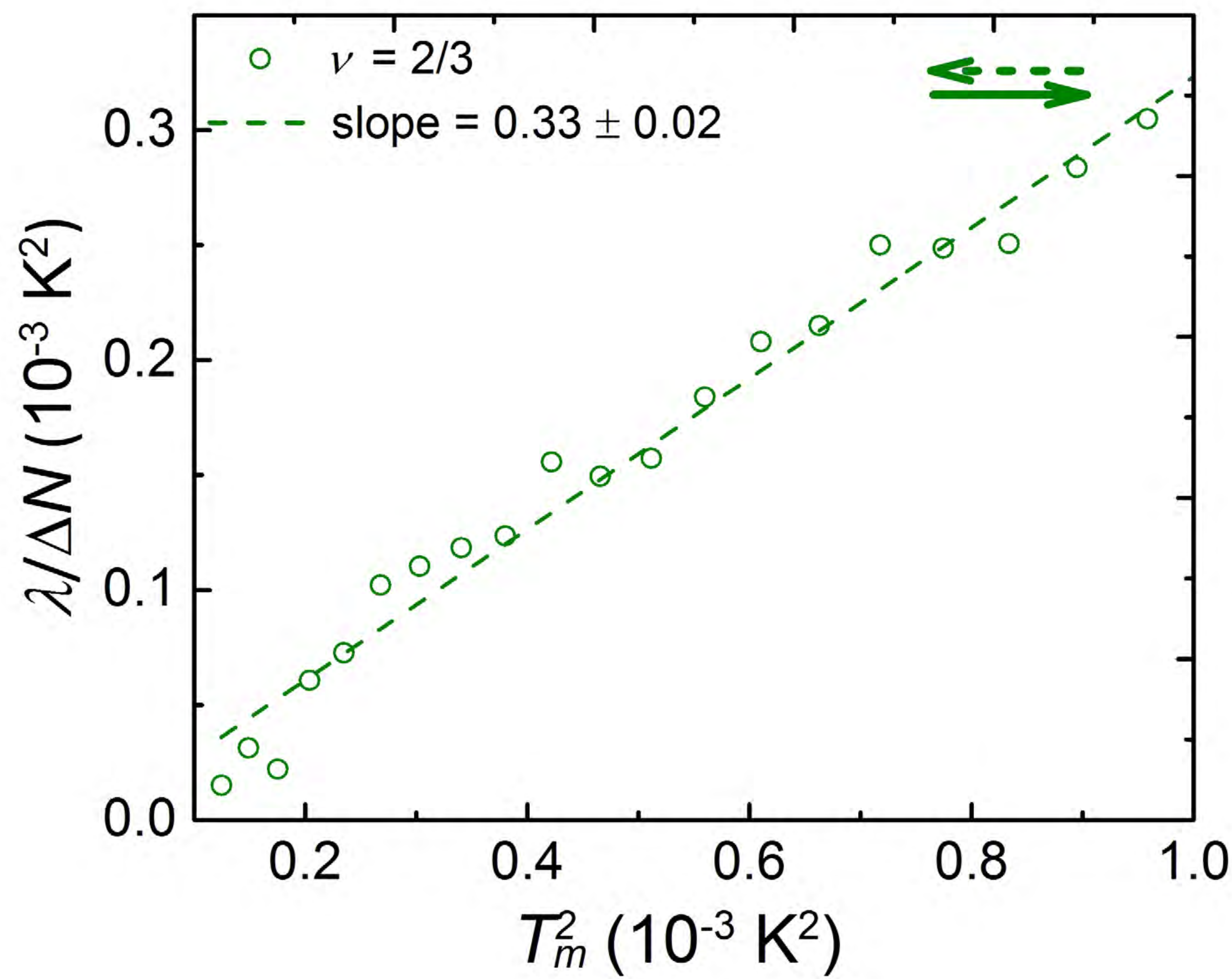
$\nu = 4/7 \rightarrow -2\kappa_0$ **1** down charge - **3** ***neutrals*** up

ν = 2/3 ...... why K = 0 ?



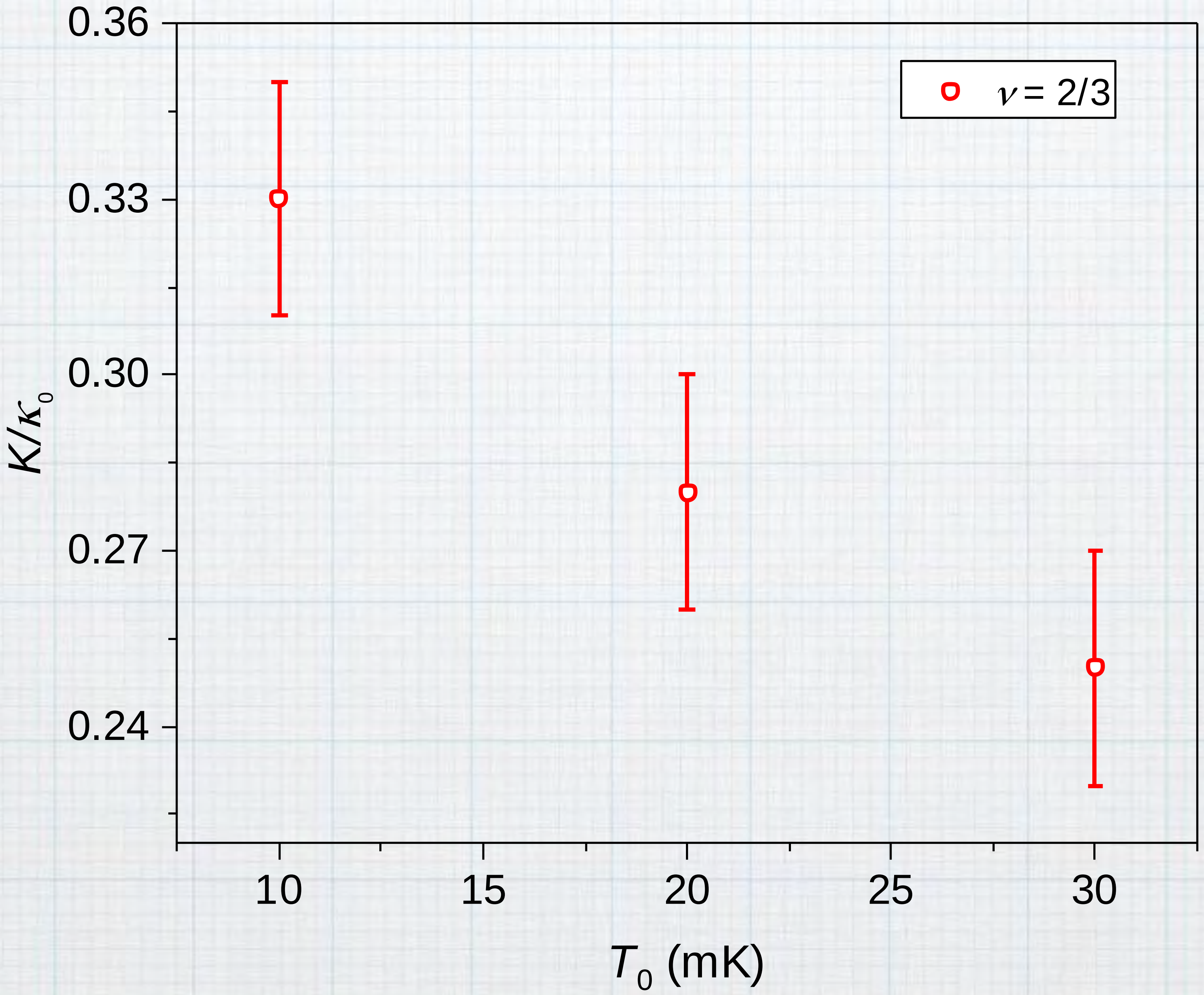
<u>equal</u> number of **down** and **up** modes

full equilibration ONLY at large length…..**all** emitted heat **returns**

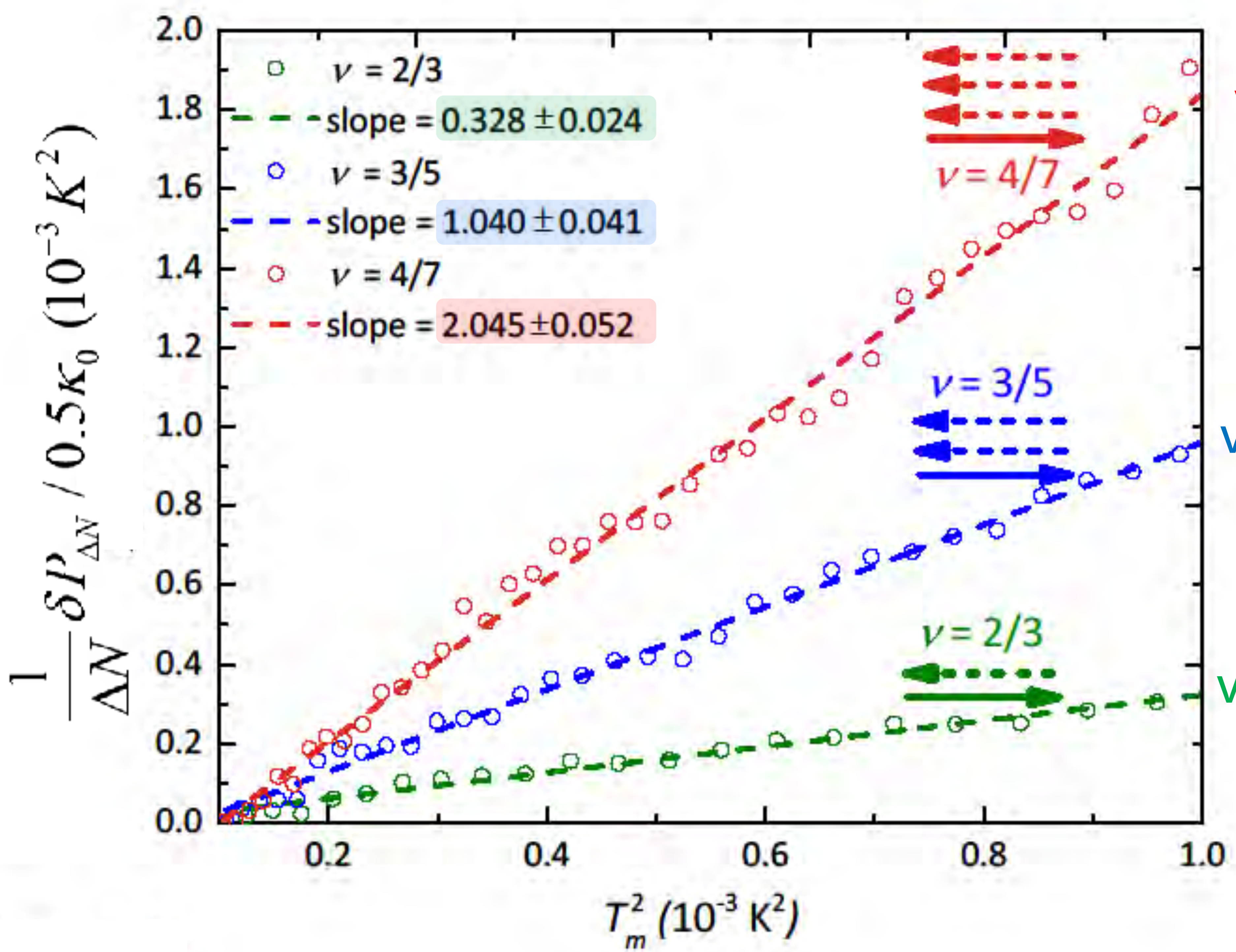


ν = 2/3
slope = 0.33 ± 0.02
0.0
0.1
0.2
0.3
λ/ΔN (10^-3 K^2)
0.2
0.4
0.6
0.8
1.0
T_m^2 (10^-3 K^2)

Temperature dependence



hole-states with more upstream neutral modes

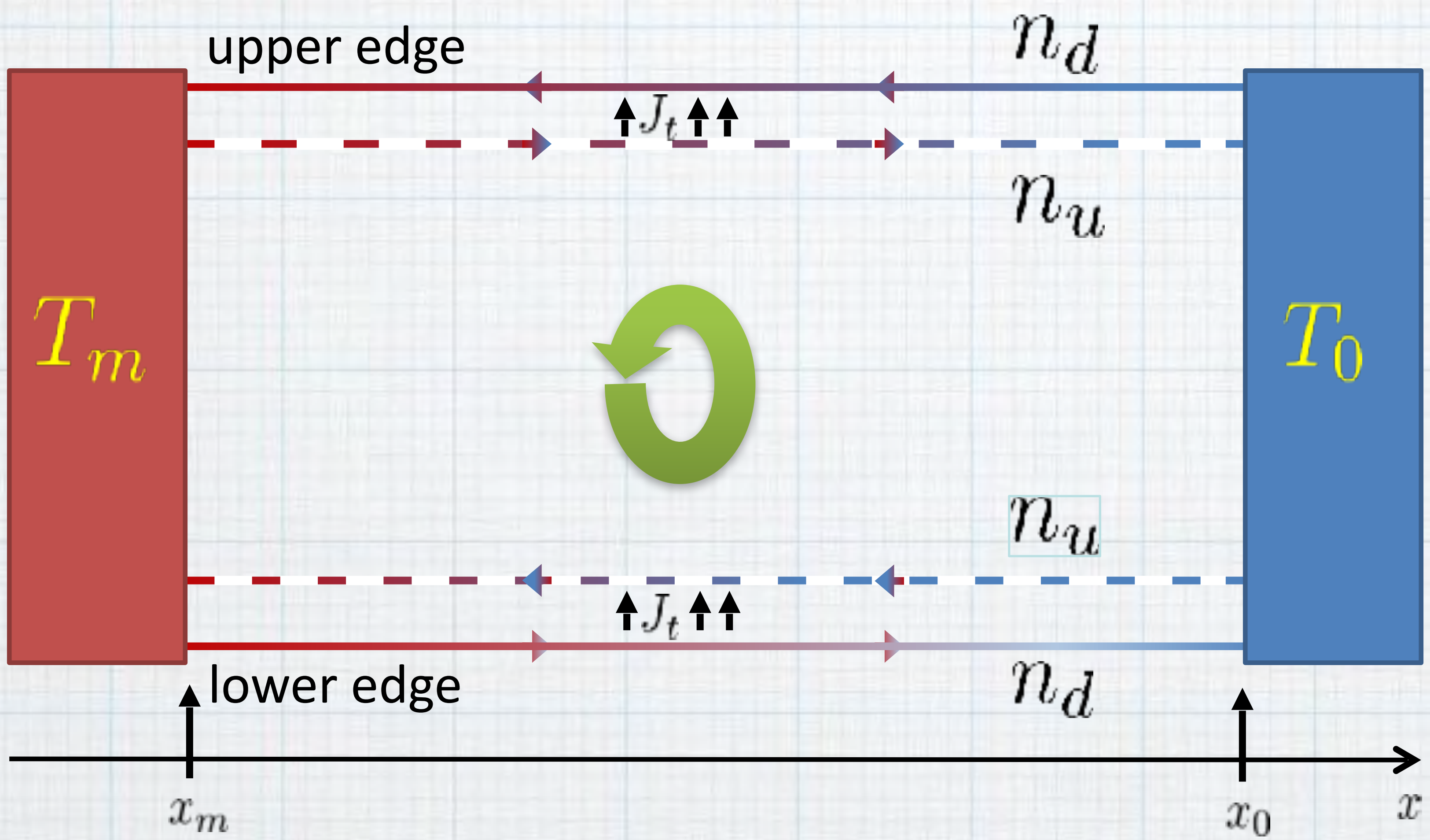


ν =4/7 → |-2κ$_0$|

ν =3/5 → |-κ$_0$|

ν =2/3 → κ >0

calculating T (x) & K ...... ν =2/3



$n_d = n_u = 1$

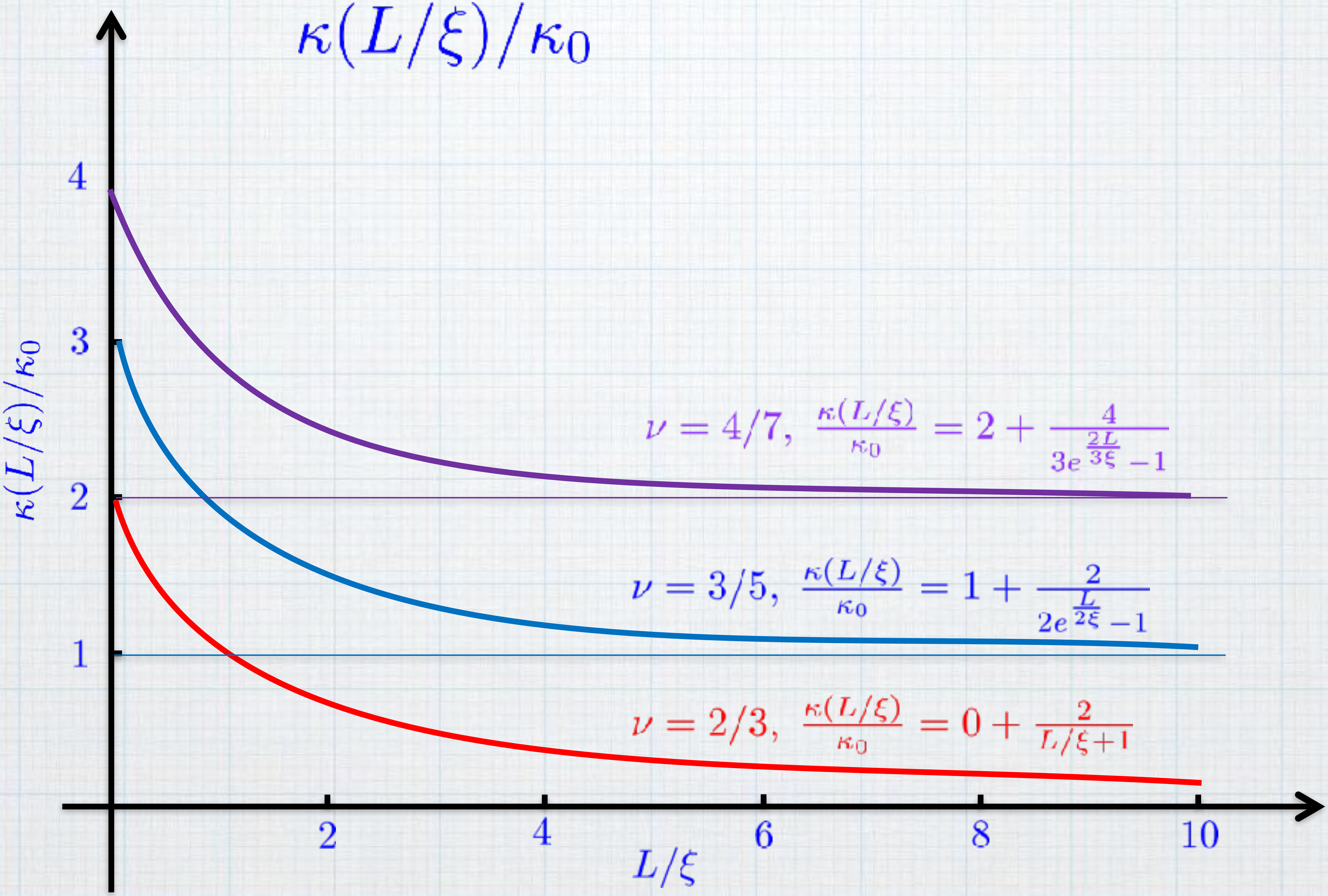
$$J = KT^2$$

$$0.5 n_u \kappa_0 \partial_x T_u^2(x) = -j_t(x)$$

$$0.5 n_d \kappa_0 \partial_x T_d^2(x) = -j_t(x)$$

Newton's law of cooling

$$j_t(x) = \frac{\kappa_0}{2\xi_T}\left(T_d^2(x) - T_u^2(x)\right)$$


$\kappa(L/\xi)/\kappa_0$
4
3
2
1
$\nu = 4/7,\ \frac{\kappa(L/\xi)}{\kappa_0} = 2 + \frac{4}{3e^{\frac{2L}{3\xi}} - 1}$
$\nu = 3/5,\ \frac{\kappa(L/\xi)}{\kappa_0} = 1 + \frac{2}{2e^{\frac{L}{2\xi}} - 1}$
$\nu = 2/3,\ \frac{\kappa(L/\xi)}{\kappa_0} = 0 + \frac{2}{L/\xi + 1}$
2
4
6
8
10
L/ξ

Summary :

1D electron modes

1D fractional modes

1D neutral modes

quantized thermal conductance

LETTER

doi:10.1038/nature22052

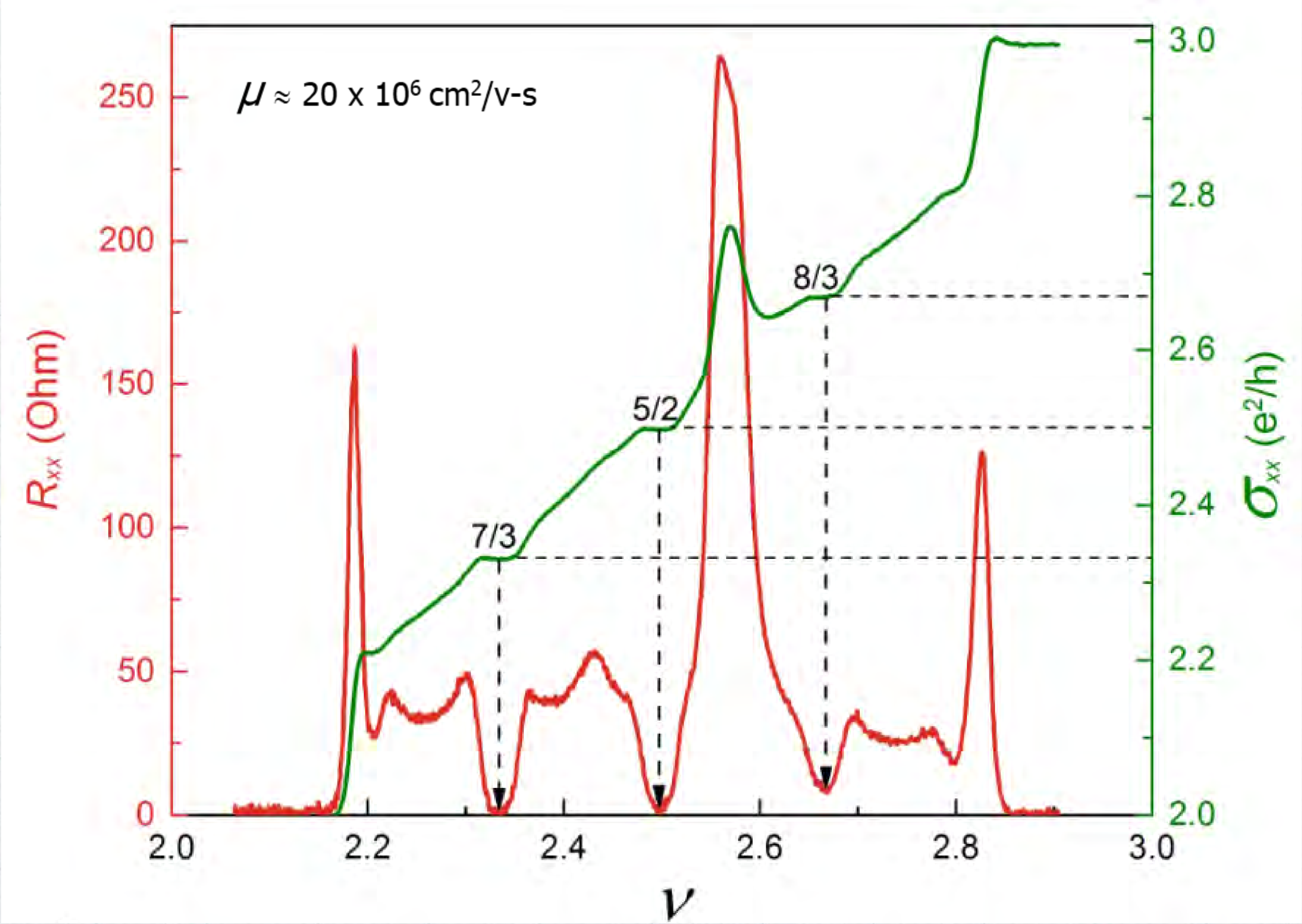
Observed quantization of anyonic heat flow

Mitali Banerjee[1], Moty Heiblum[1], Amir Rosenblatt[1], Yuval Oreg[1], Dima E. Feldman[2], Ady Stern[1] & Vladimir Umansky[1]

fractional states in first excited Landau level

$\nu = 2 + \eta$

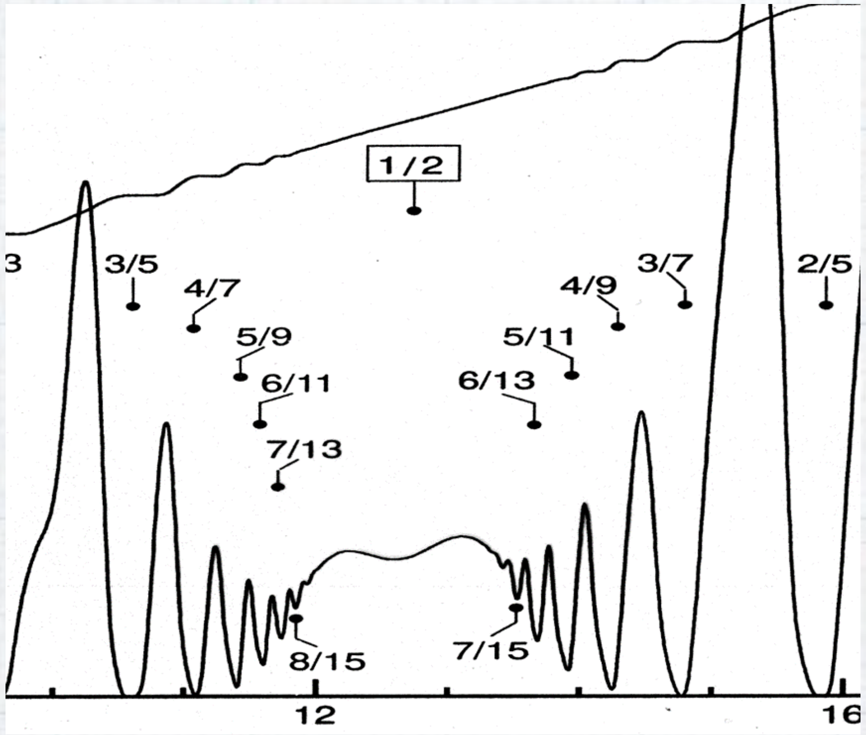
$\nu = 7/3, \ 5/2, \ 8/3$

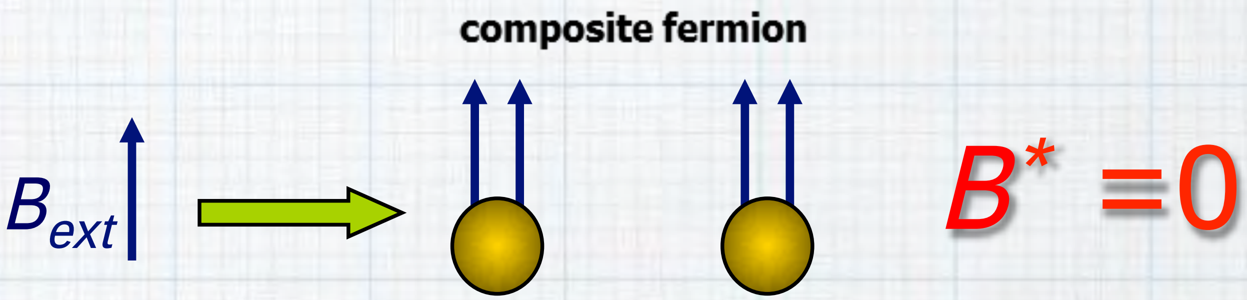


μ ≈ 20 x 10^6 cm^2/v-s
250
200
150
100
50
0
Rxx (Ohm)
3.0
2.8
2.6
2.4
2.2
2.0
σxx (e^2/h)
7/3
5/2
8/3
2.0
2.2
2.4
2.6
2.8
3.0
ν

ν = 5/2 state

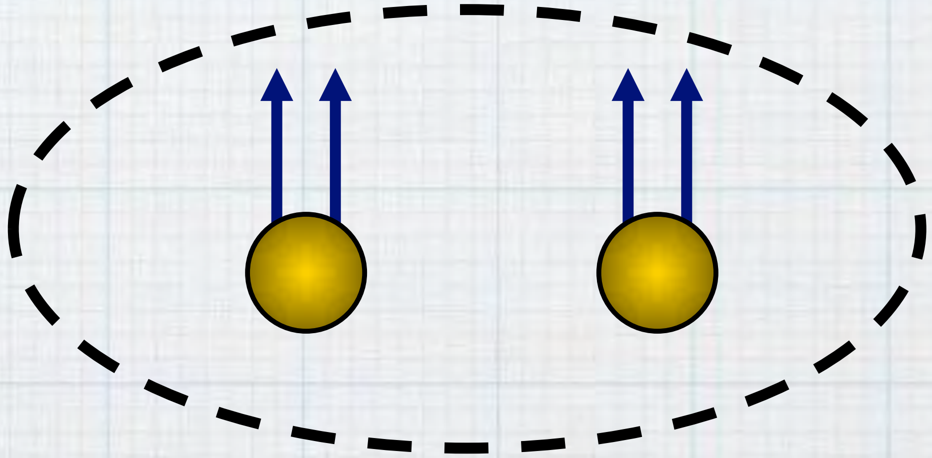
Moore - Read 1991





at ν = 5/2......R_{xx}=0

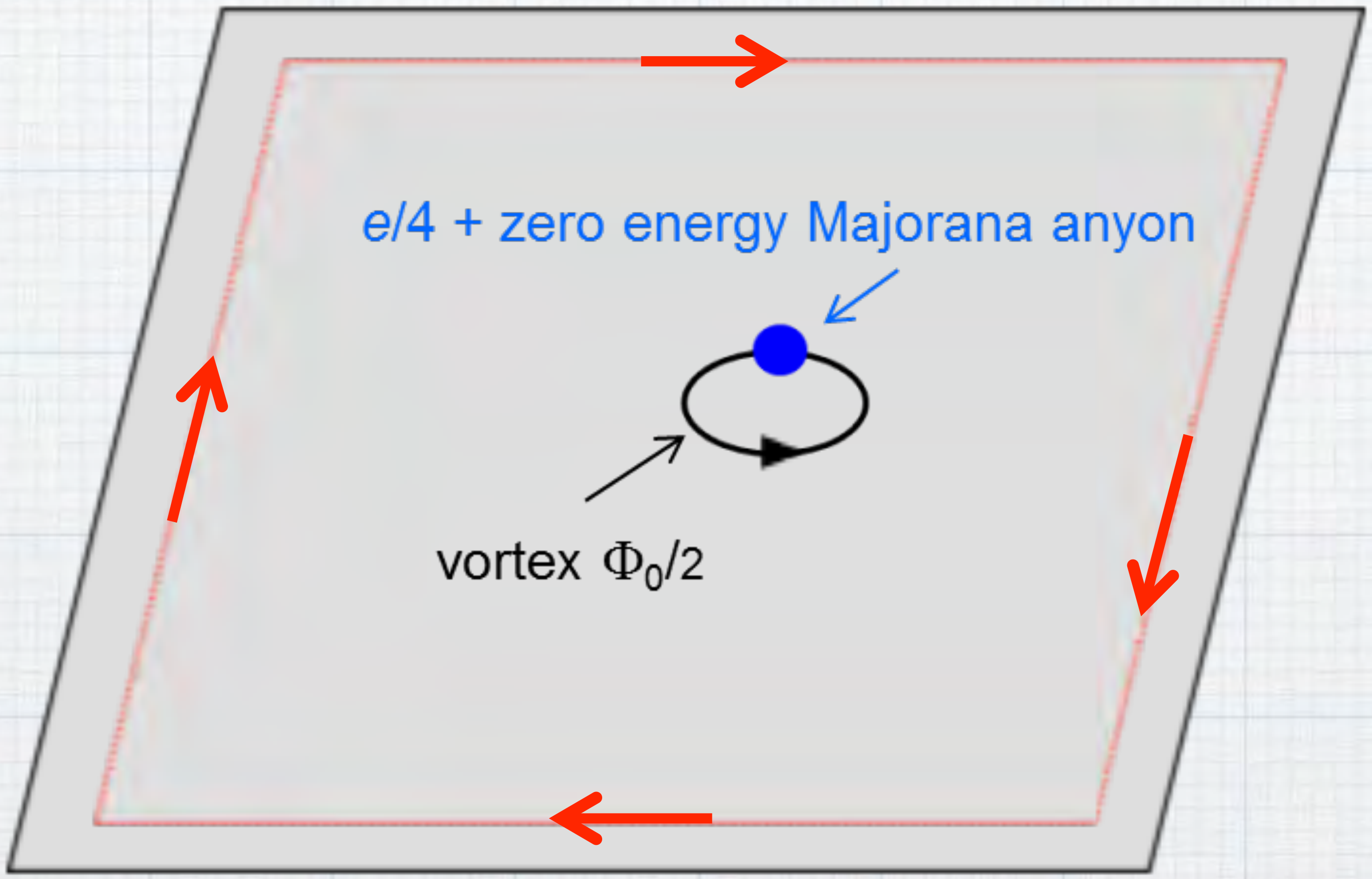
p-wave Cooper pair



BCS of polarized composite fermions
w/ odd orbital angular momentum

5/2 state Moore – Read, Pfaffian state

bulk – edge correspondence



1D edge liquid of $e/4$ + Majorana anyon

Majorana → half fermion…. $K = \kappa_0 / 2$

already known for ν =5/2

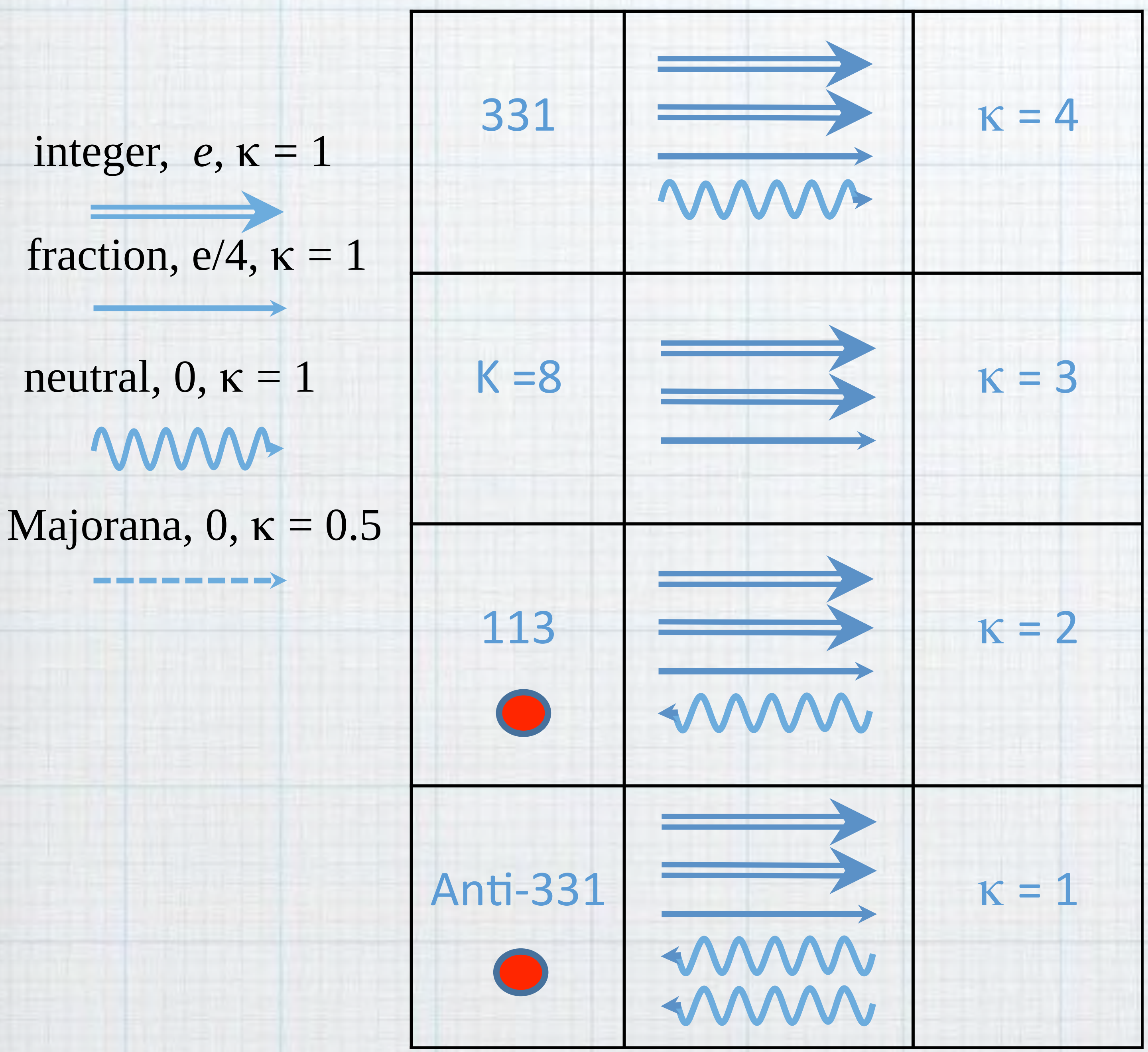
- charge e /4
- upstream neutral modes
- spin polarized

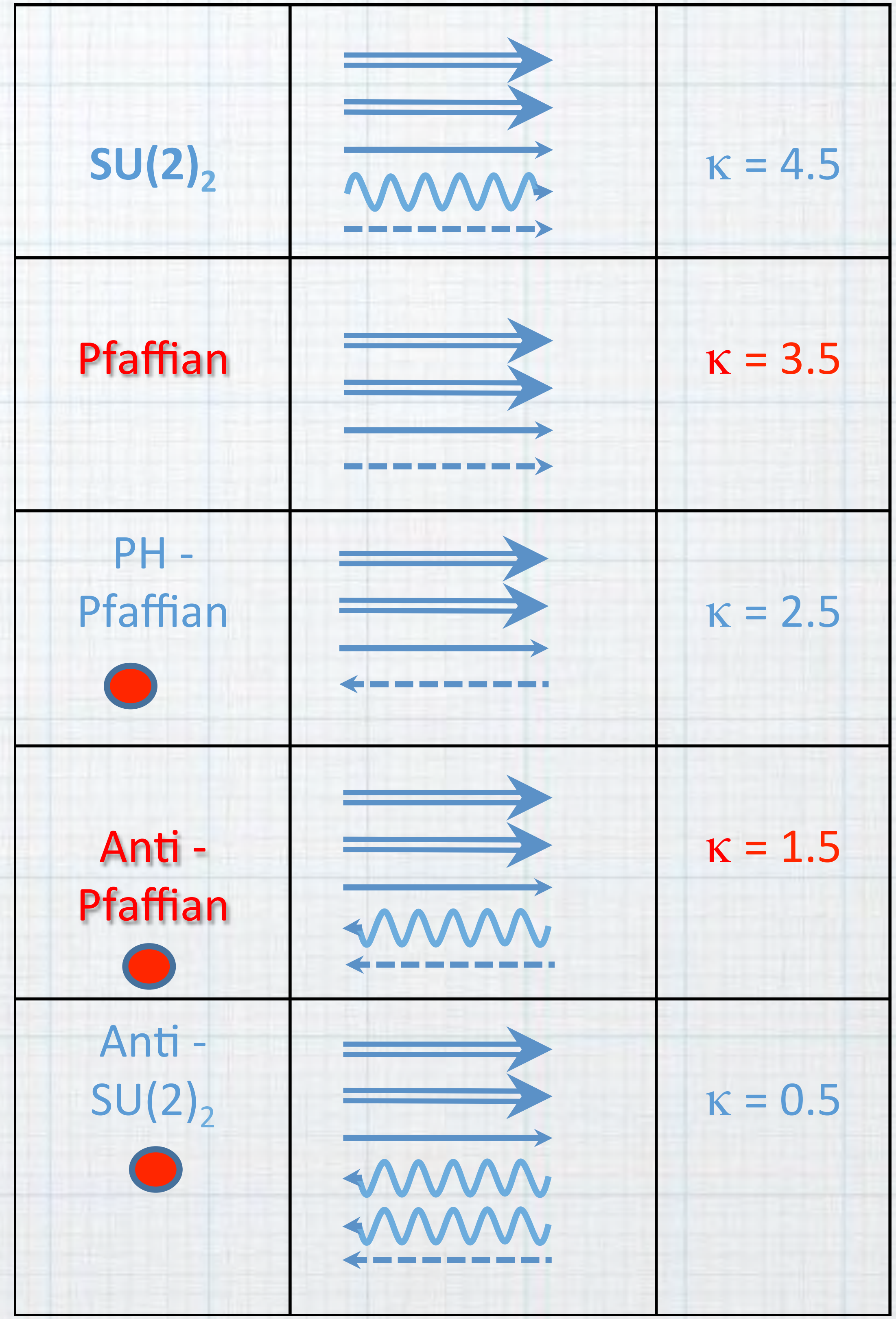
abelian or non-abelian ?

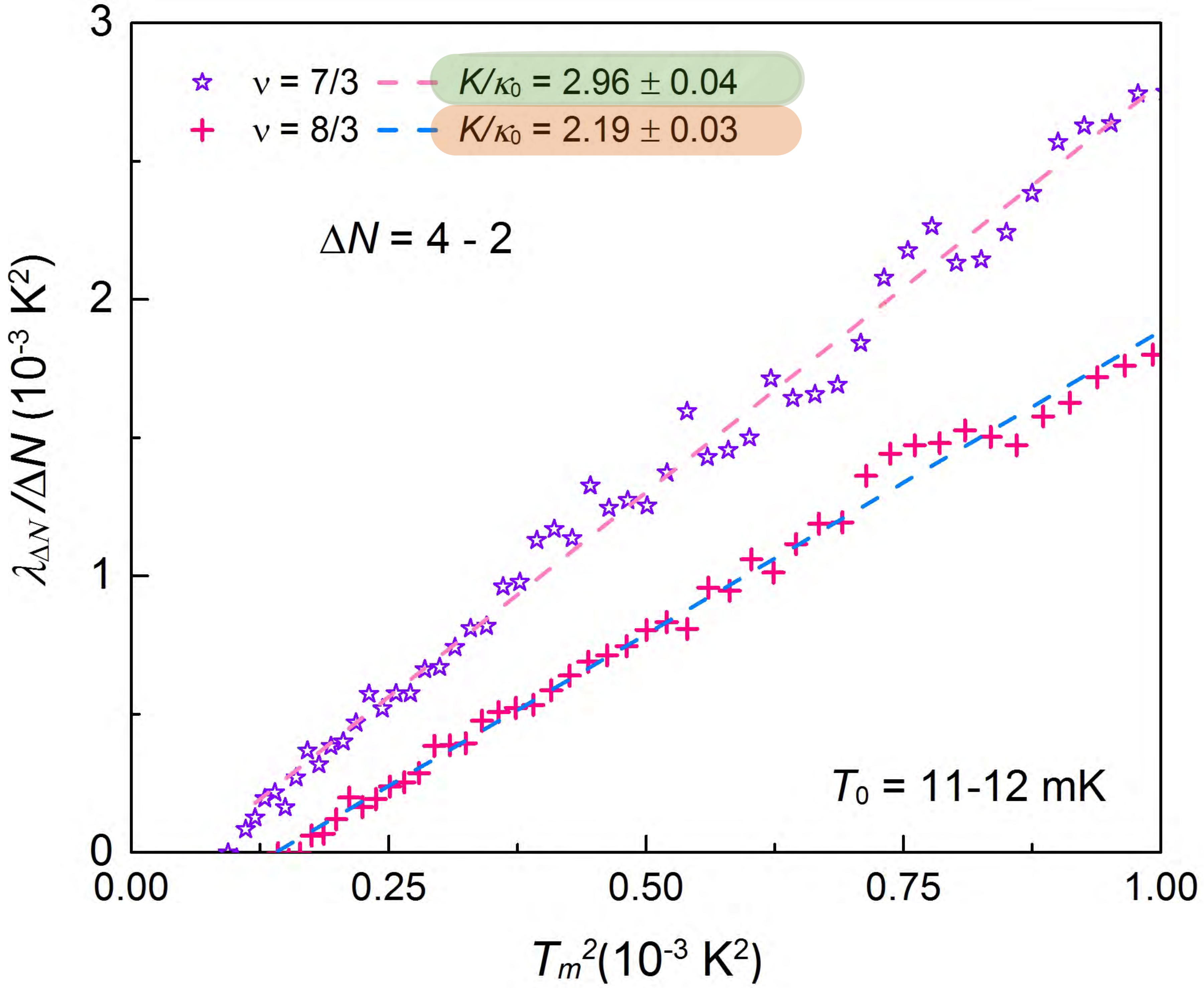
fractional state............ ***ν* = 5/2**

a

if non-abelian......... $K = (n \pm 0.5)\kappa_0$







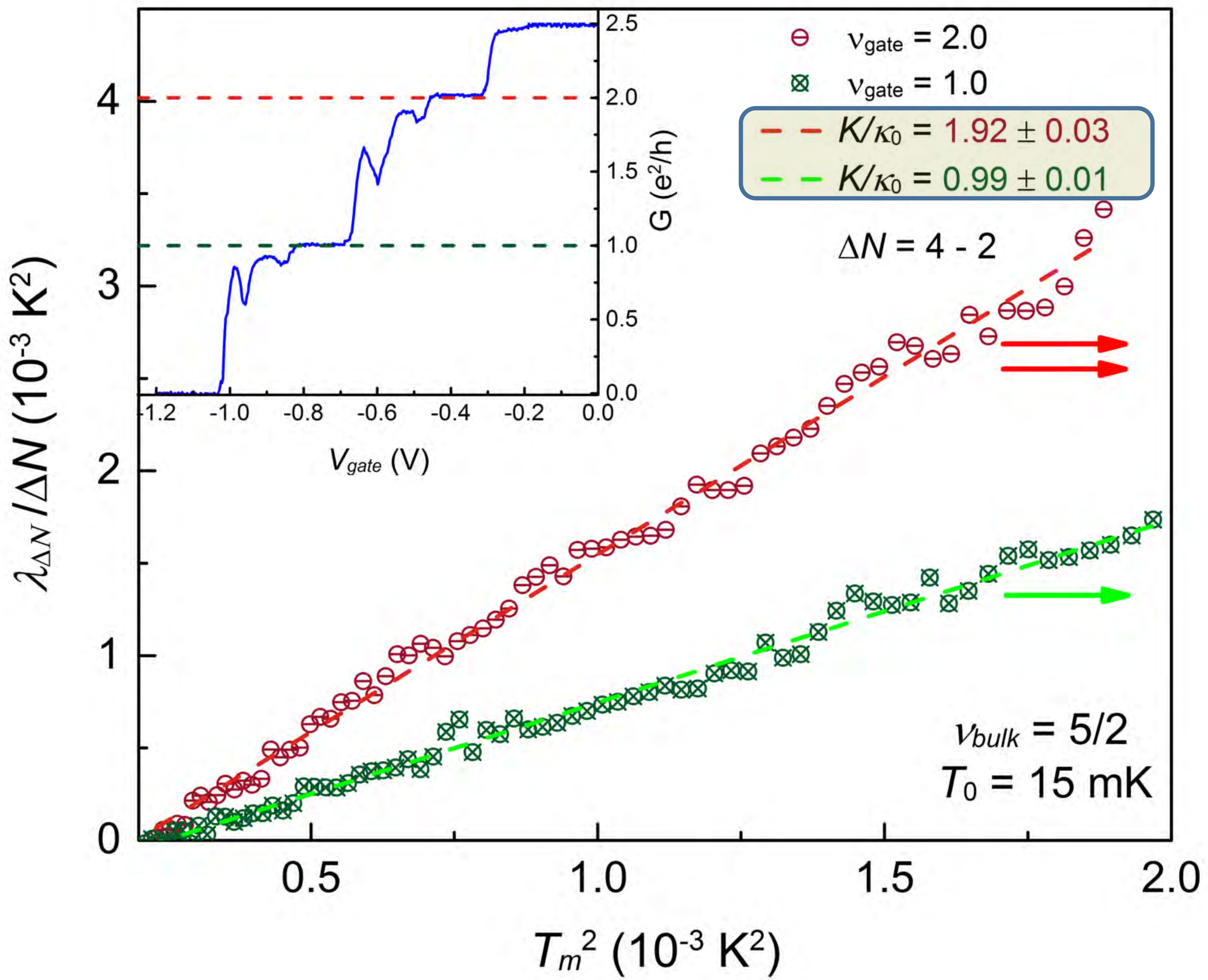
ν = 7/3
K/κ0 = 2.96 ± 0.04
ν = 8/3
K/κ0 = 2.19 ± 0.03
ΔN = 4 - 2
T0 = 11-12 mK
λΔN /ΔN (10-3 K2)
Tm2(10-3 K2)
0
1
2
3
0.00
0.25
0.50
0.75
1.00

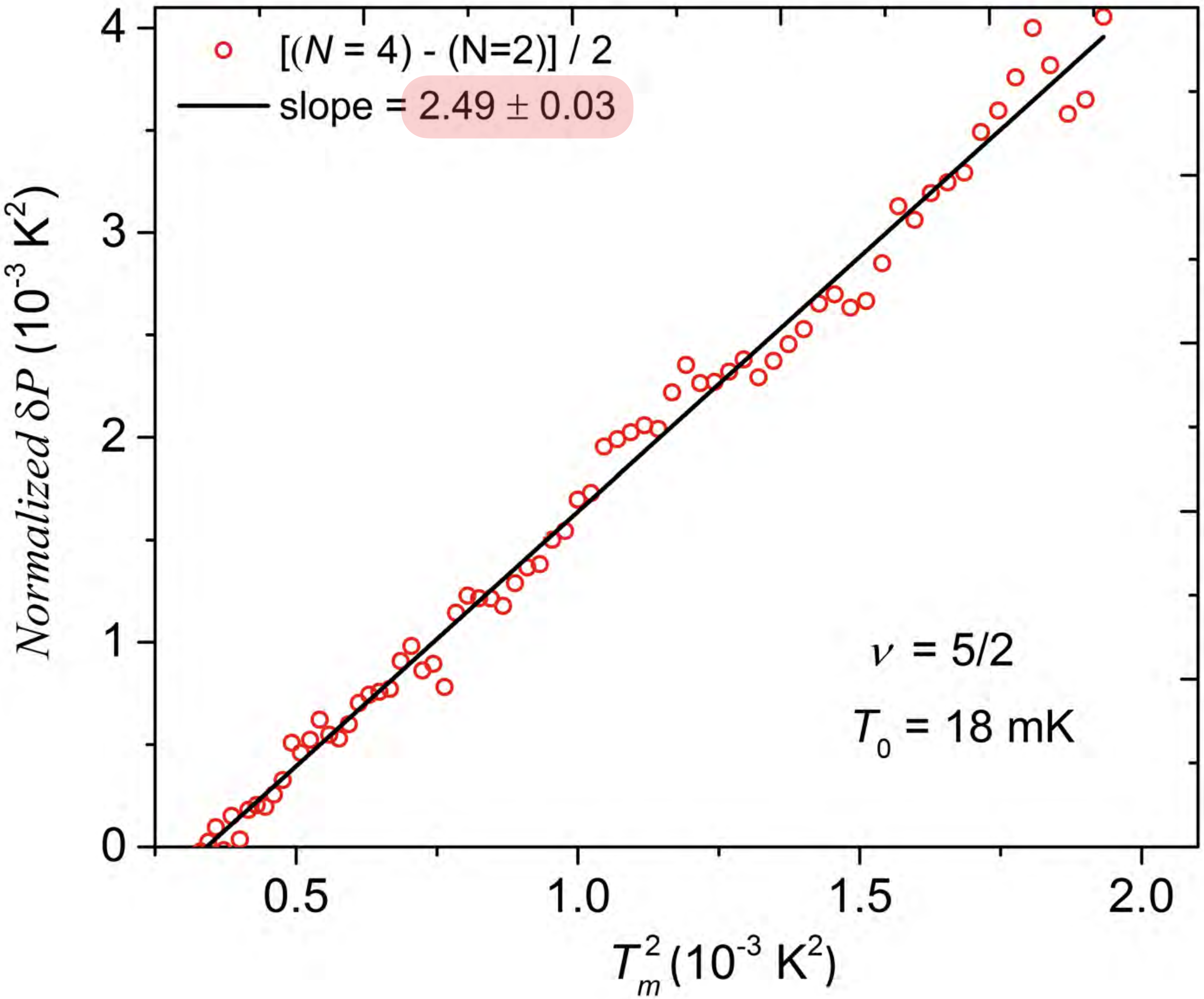
measured

$\nu = 7/3$	$\nu = 2 + 1/3$	particle like, downstream	$K = 3\kappa_0$
$\nu = 8/3$	$\nu = 2 + 2/3$	hole-like, down - up	$K = (2+\varepsilon)\kappa_0$

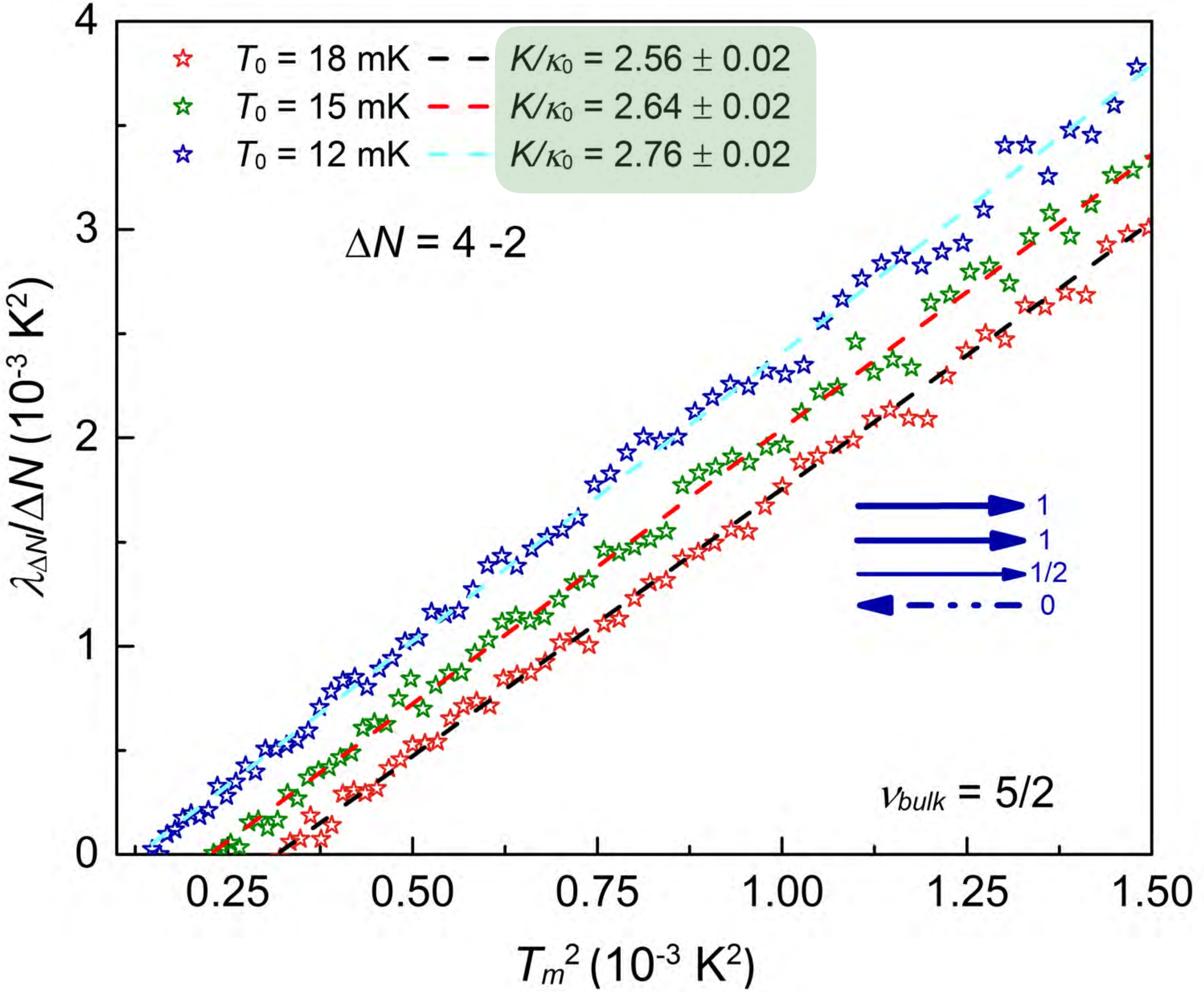
$\nu = 5/2$

measuring $\nu = 1,2$ @ $\nu_B = 5/2$

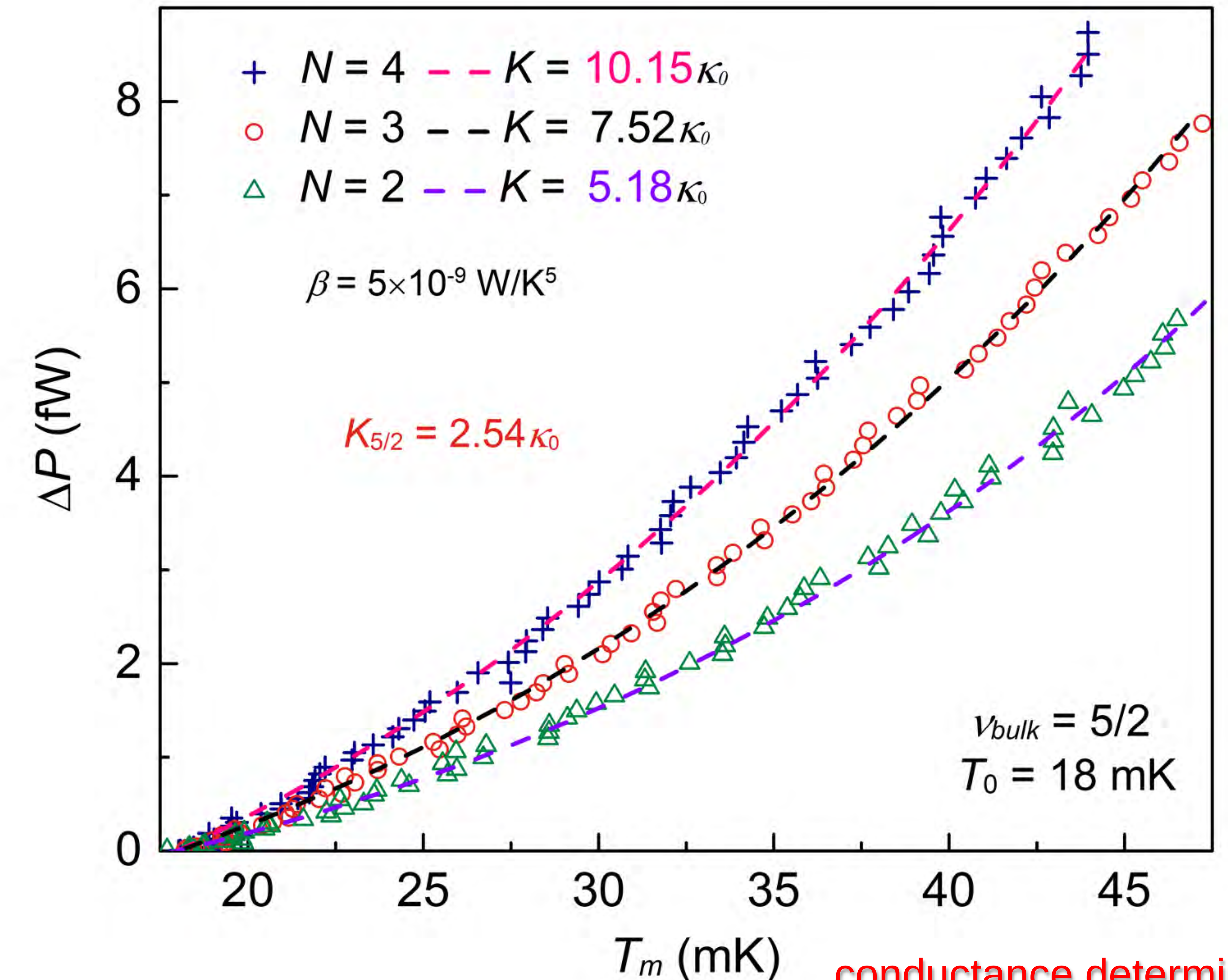




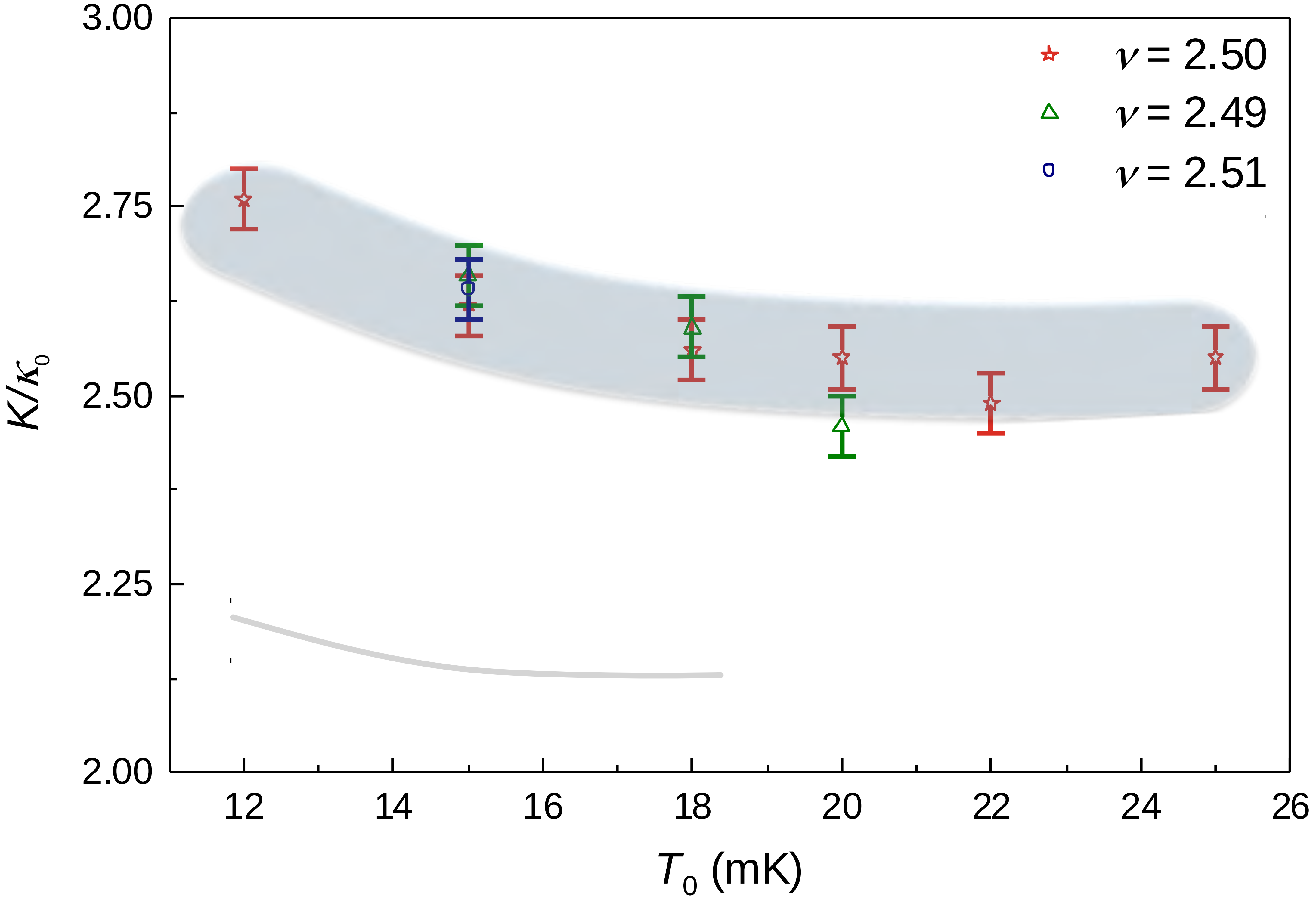
[(N = 4) - (N=2)] / 2
slope = 2.49 ± 0.03
ν = 5/2
T0 = 18 mK
Normalized δP (10-3 K2)
Tm2 (10-3 K2)
0
1
2
3
4
0.5
1.0
1.5
2.0



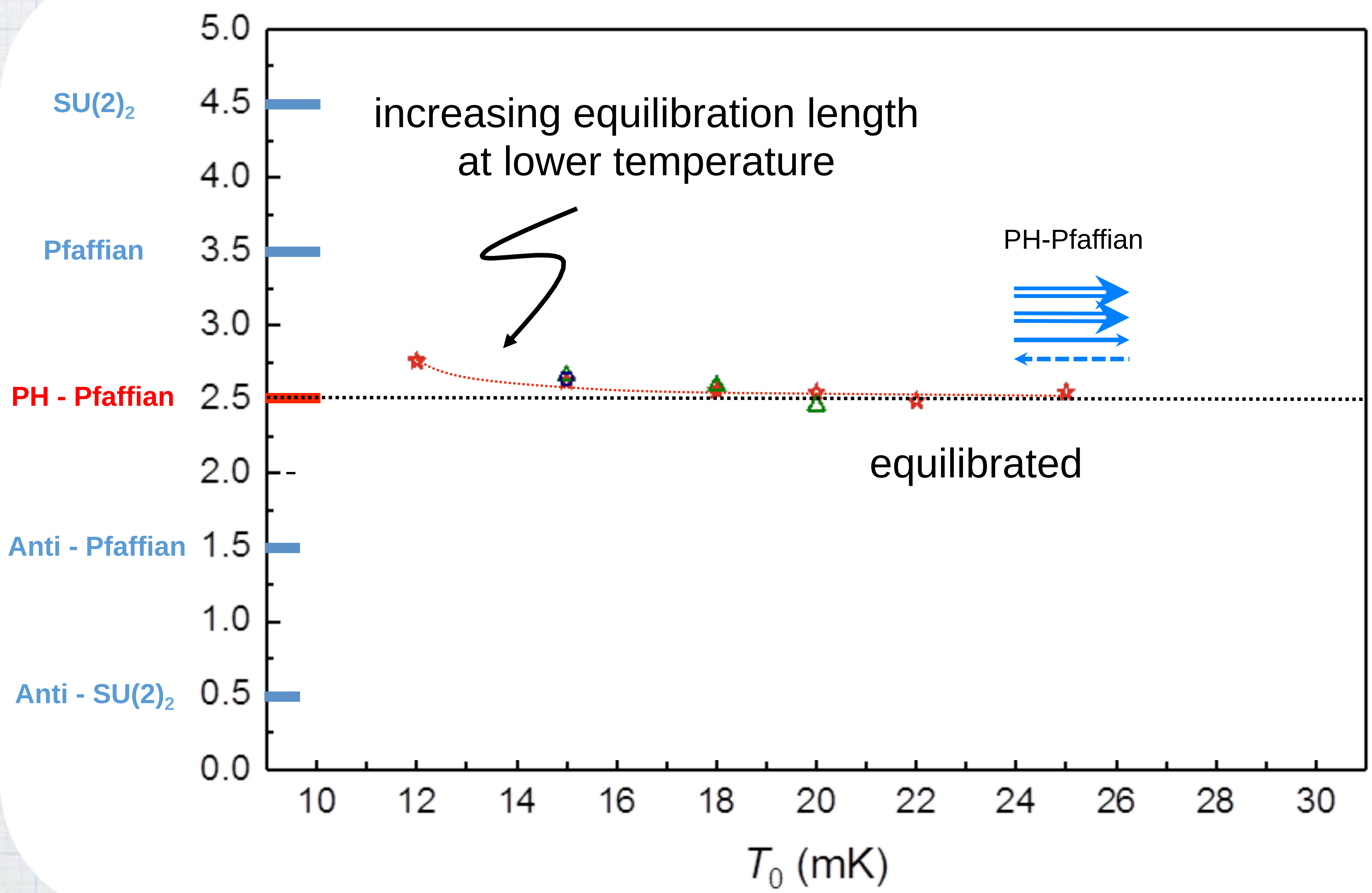
T_0 = 18 mK
K/κ_0 = 2.56 ± 0.02
T_0 = 15 mK
K/κ_0 = 2.64 ± 0.02
T_0 = 12 mK
K/κ_0 = 2.76 ± 0.02
ΔN = 4 -2
1
1
1/2
0
ν_{bulk} = 5/2
$\lambda_{\Delta N}/\Delta N$ (10^{-3} K^2)
T_m^2 (10^{-3} K^2)
0
1
2
3
4
0.25
0.50
0.75
1.00
1.25
1.50



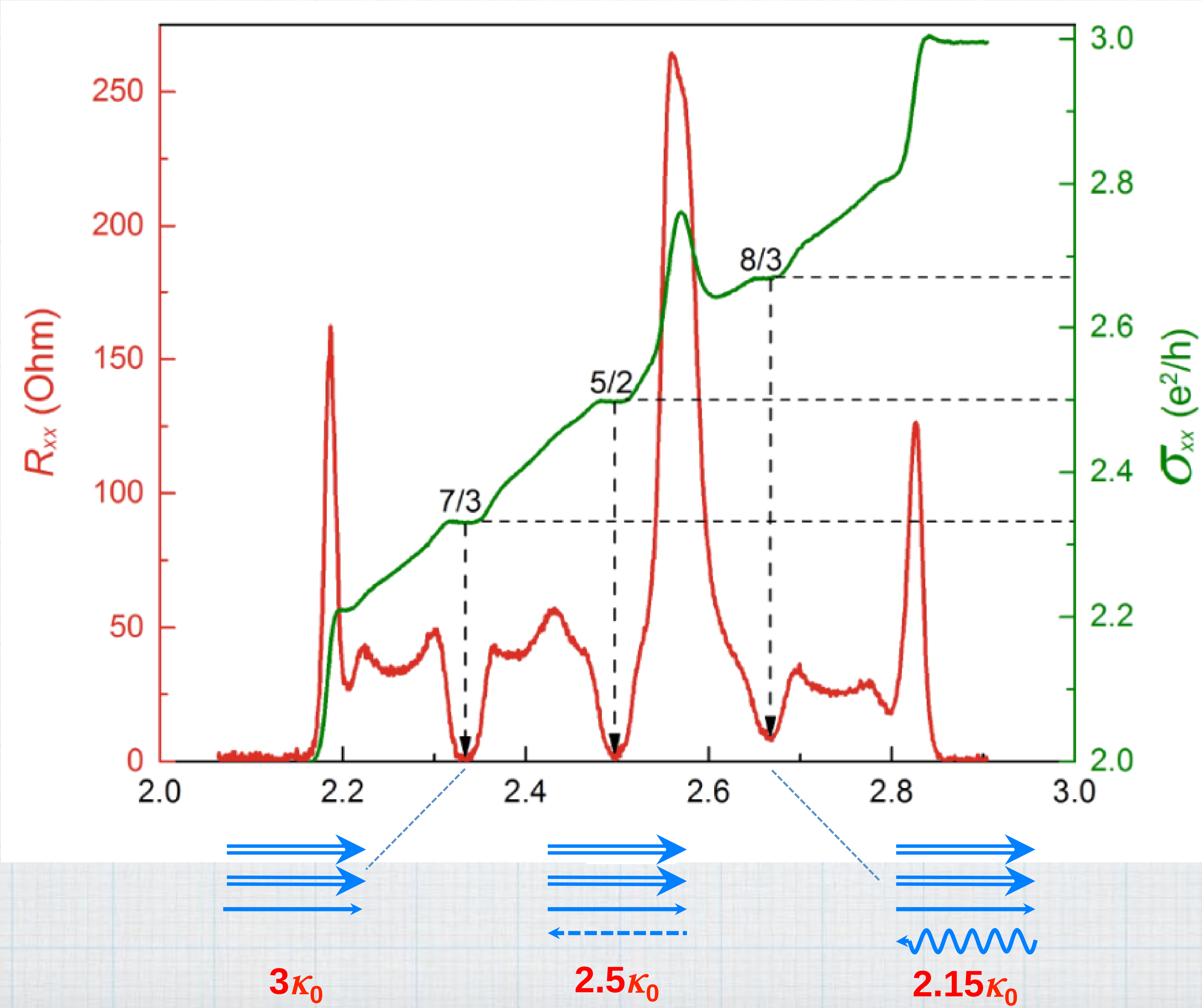
conductance determination *with* phonons contribution



3.00
2.75
2.50
2.25
2.00
K/κ_0
12
14
16
18
20
22
24
26
T_0 (mK)
$\nu = 2.50$
$\nu = 2.49$
$\nu = 2.51$



SU(2)$_2$
Pfaffian
PH - Pfaffian
Anti - Pfaffian
Anti - SU(2)$_2$
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
increasing equilibration length
at lower temperature
PH-Pfaffian
equilibrated
10
12
14
16
18
20
22
24
26
28
30
T_0 (mK)



250
200
150
100
50
0
R_{xx} (Ohm)
3.0
2.8
2.6
2.4
2.2
2.0
σ_{xx} (e^2/h)
2.0
2.2
2.4
2.6
2.8
3.0
7/3
5/2
8/3
$3\kappa_0$
$2.5\kappa_0$
$2.15\kappa_0$

Theory of Disorder-Induced Half-Integer Thermal Hall Conductance

David F. Mross, Yuval Oreg, Ady Stern, Gilad Margalit, and Moty Heiblum
Braun Center for Submicron Research, Department of Cond. Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel

Topological Order from Disorder and the Quantized Hall Thermal Metal: Possible Applications to the $\nu = 5/2$ State

Chong Wang,[1] Ashvin Vishwanath,[1] and Bertrand I. Halperin[1]
[1]*Department of Physics, Harvard University, Cambridge MA 02138, USA*

On the Interpretation of Thermal Conductance of the $\nu - 5/2$ Edge

Steven H. Simon[1]
[1]*Rudolf Peierls Centre for Theoretical Physics, 1 Keble Road, Oxford, OX1 3NP, UK*
(Dated: January 31, 2018)

Theory of Disordered $\nu = 5/2$ Quantum Thermal Hall State: Emergent Symmetry and Phase Diagram

Biao Lian[1] and Juven Wang[2]
[1] *Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA*
[2]*School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA*

ν = 5/2……..likely non-abelian

measuring thermal conductance

reveals hidden information

ARTICLE

https://doi.org/10.1038/s41586-018-0184-1

Observation of half-integer thermal Hall conductance

Mitali Banerjee[1], Moty Heiblum[1]*, Vladimir Umansky[1], Dima E. Feldman[2], Yuval Oreg[1] & Ady Stern[1]

Thank you !!!

Future Directions

Starting with K

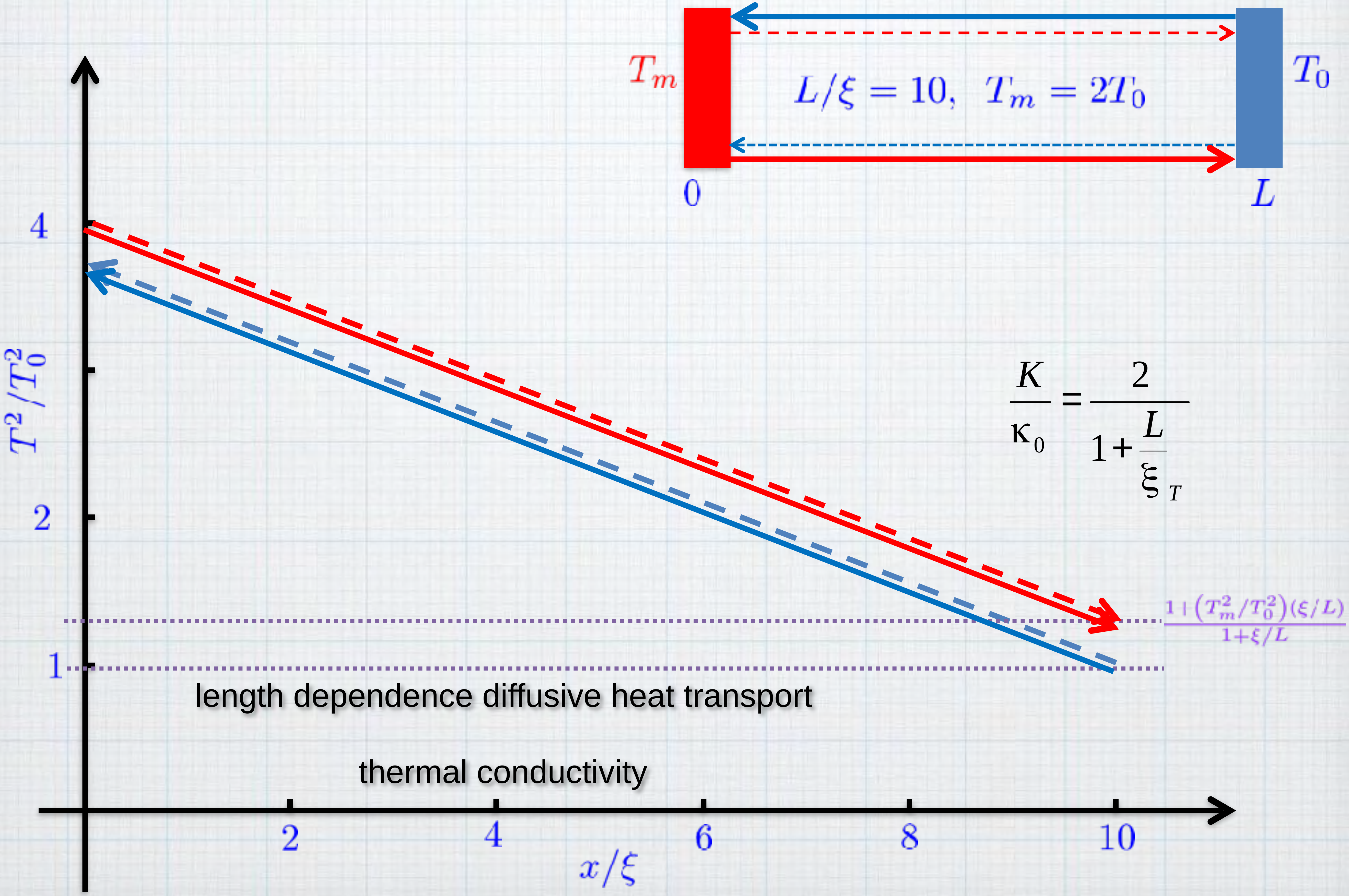
- Measuring K at ν=5/2 at short distances – aided with noise measurements to check down and up neutral modes
- Doing the same in graphene (and bi-layer graphene) – as flakes are small
- Measuring K at ν=5/2 at different *B*'s and different *n*'s – with aid of a back gate – testing if K is universal in this state or depends on parameters
- Studying K at ν=12/5. Not easy as accuracy has to be better than $0.5k_0$.
- Studying ν=7/2 – also predicted to be non-abelian (but our quick measurement didn't see it…)

Interference

- Can we prevent neutral modes in GaAs 2DEG?
- If we can, looking for interference
- Looking for neutral modes in graphene (and others monolayer materials…)
- If no neutral modes, look for interference in graphene – first integer and fractions

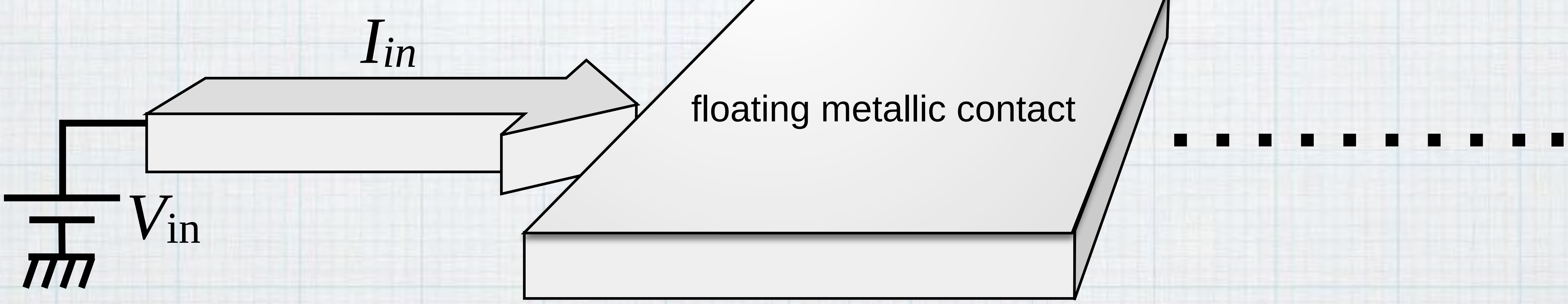
Thank you !!!

temperature profile, ν =2/3

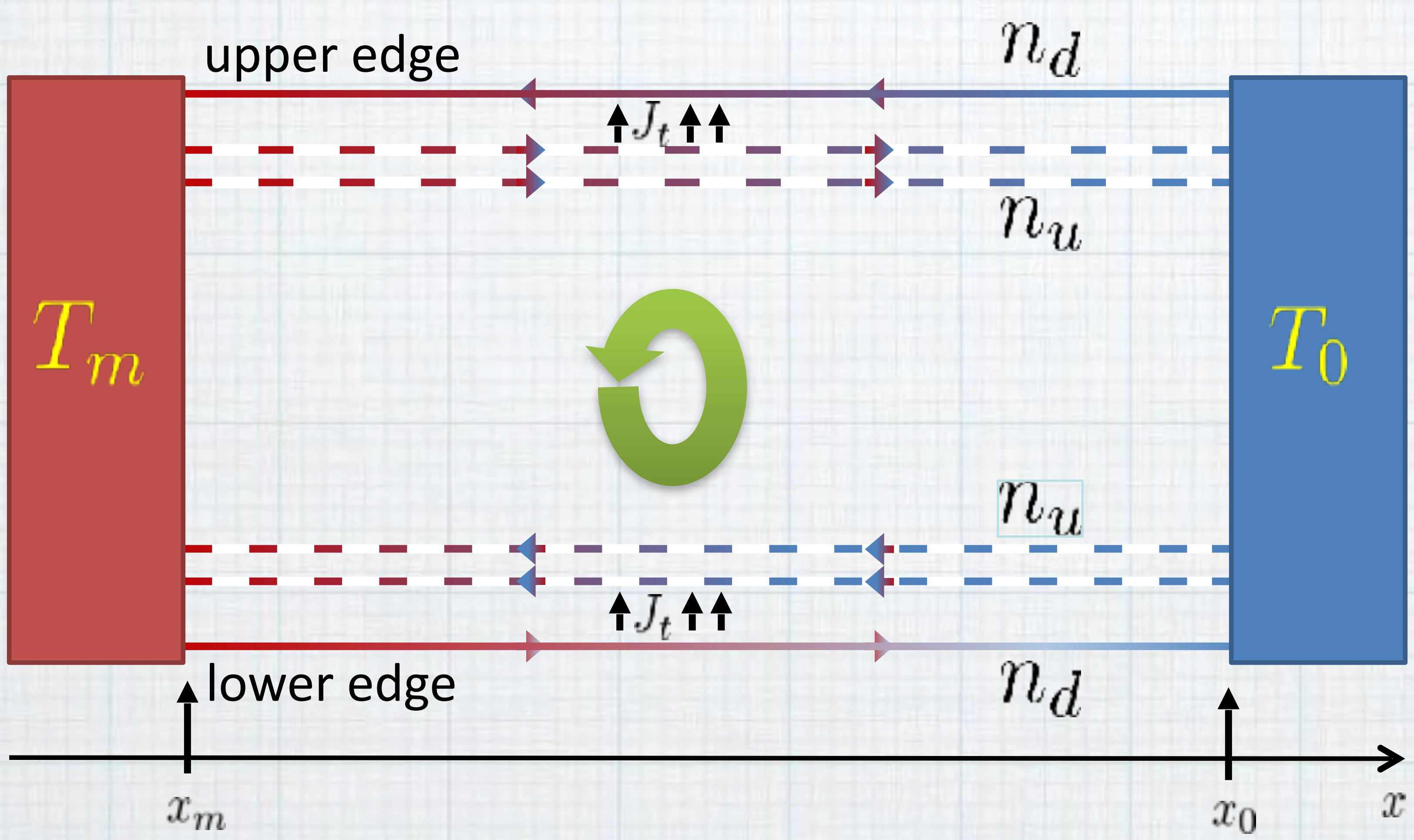


heating the reservoir

$$P_{in} = \frac{I_{in}^2}{2G_H}$$



calculating T (x) & K …… *v* =3/5



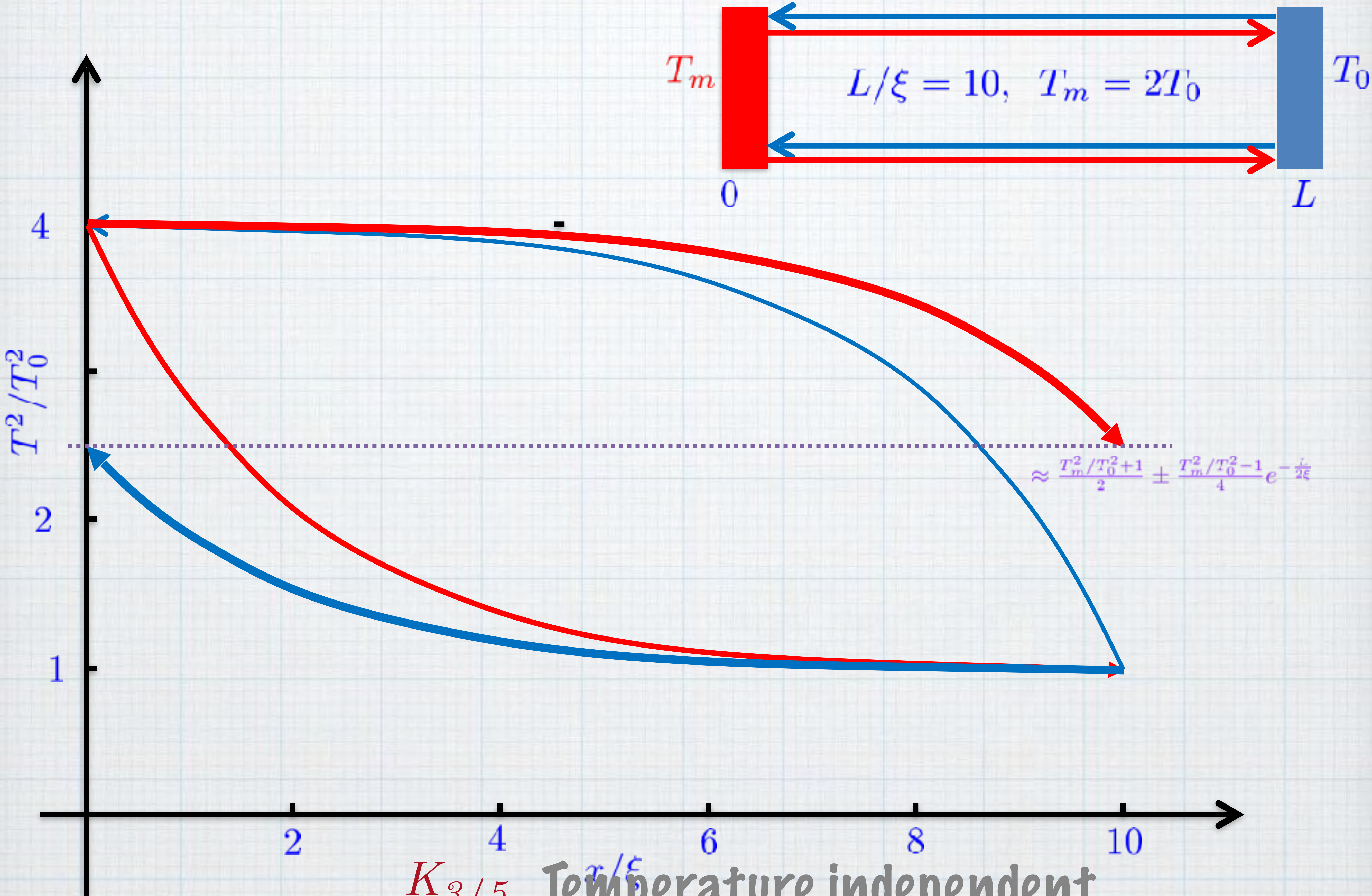
$n_d = 1 \quad n_u = 2$

$$J = KT^2$$

$$0.5 n_u \kappa_0 \partial_x T_u^2(x) = -j_t(x)$$

$$0.5 n_d \kappa_0 \partial_x T_d^2(x) = -j_t(x)$$

temperature profile, ν =3/5



$K_{3/5}$ Temperature independent

difficulties due to structure:

- ‘bulk heat conductance’…..free electrons in the donor layers
- poor contact of the floating reservoir – hence, reflections
- instability of QPC’s

MH

measured

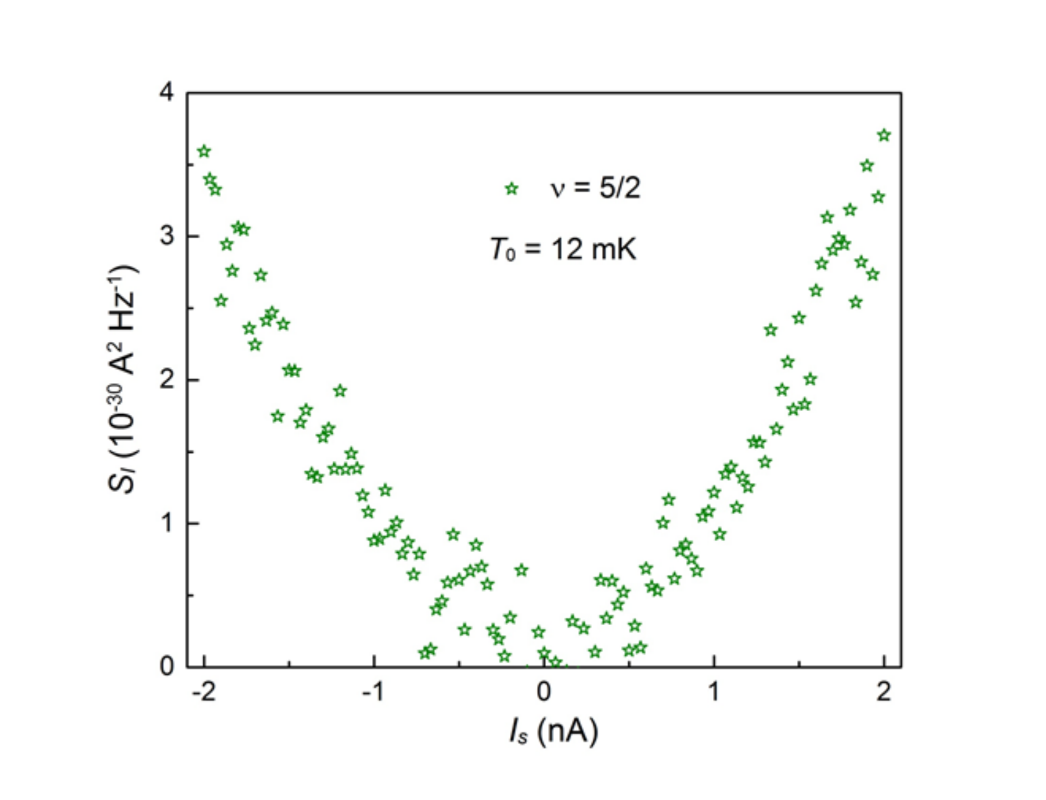
$\nu = 7/3$	$\nu = 2 + 1/3$	particle like, downstream	$K = 3\kappa_0$
$\nu = 8/3$	$\nu = 2 + 2/3$	hole-like, down + up	$K = (2+\varepsilon)\kappa_0$

- what do we know ?..........$\nu = 5/2$ $\nu = 2 + ½$

  ✓ quasiparticle charge $e^* = e/4$

  ✓ upstream energy modes

  ✓ spin polarized



$K = ?$

Points of consideration:

* noiseless source current (DC I_{in} -> in most cases)
* electrons fully equilibrate in the floating contact (with T_m)
* outgoing currents only carry J-N noise (low contact resistance)
* measurements at low temperature ($J_{e\text{-}ph} << J_e$)
* no bulk energy modes exist (may increase apparent conductance)
* required length of arms (allowing temperature equilibration)

ν =5/2 state .... if non-abelian $K/\kappa_0 = n + \frac{1}{2}$

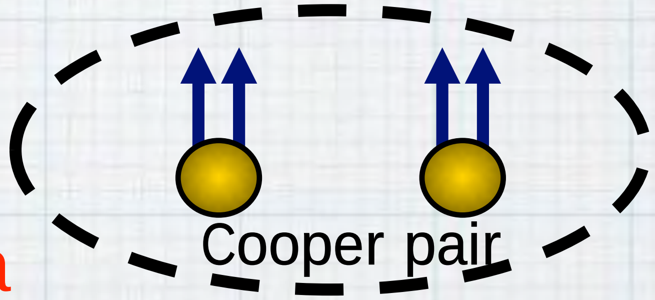
from electrons .... to non-abelian quasiparticles

* half - filled LL on top of two filled LL's.......... 2 ½ = 2 + ½

* flux attachement......spin polarized CFs
  at zero average magnetic field

$\Delta B_{1/2}$ =0

* CFs pair into Cooper pairs
  p-wave superconductor



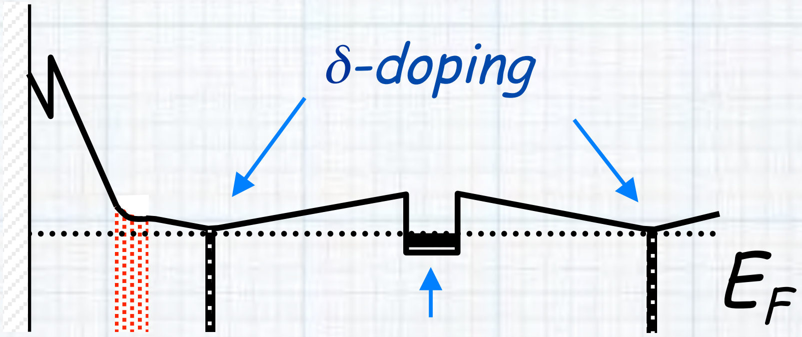
* vortices are charged.....e^*=e /4 + Majorana

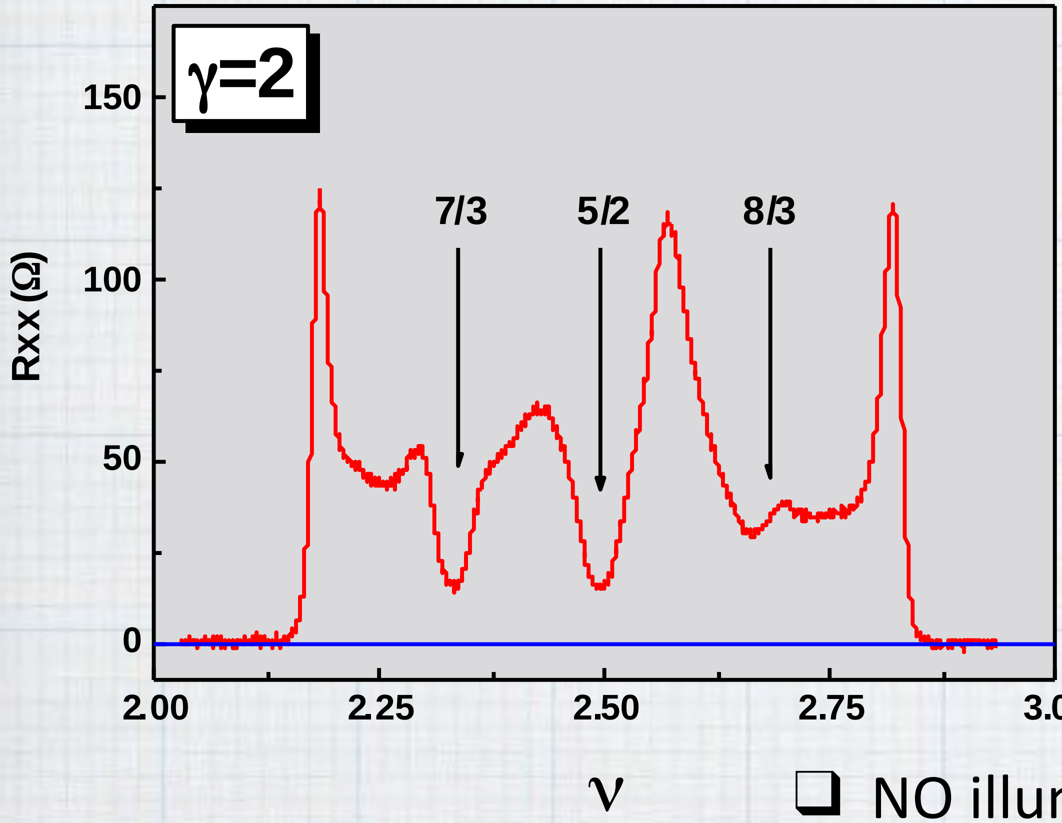
* chiral edge modes: charged + Majorana

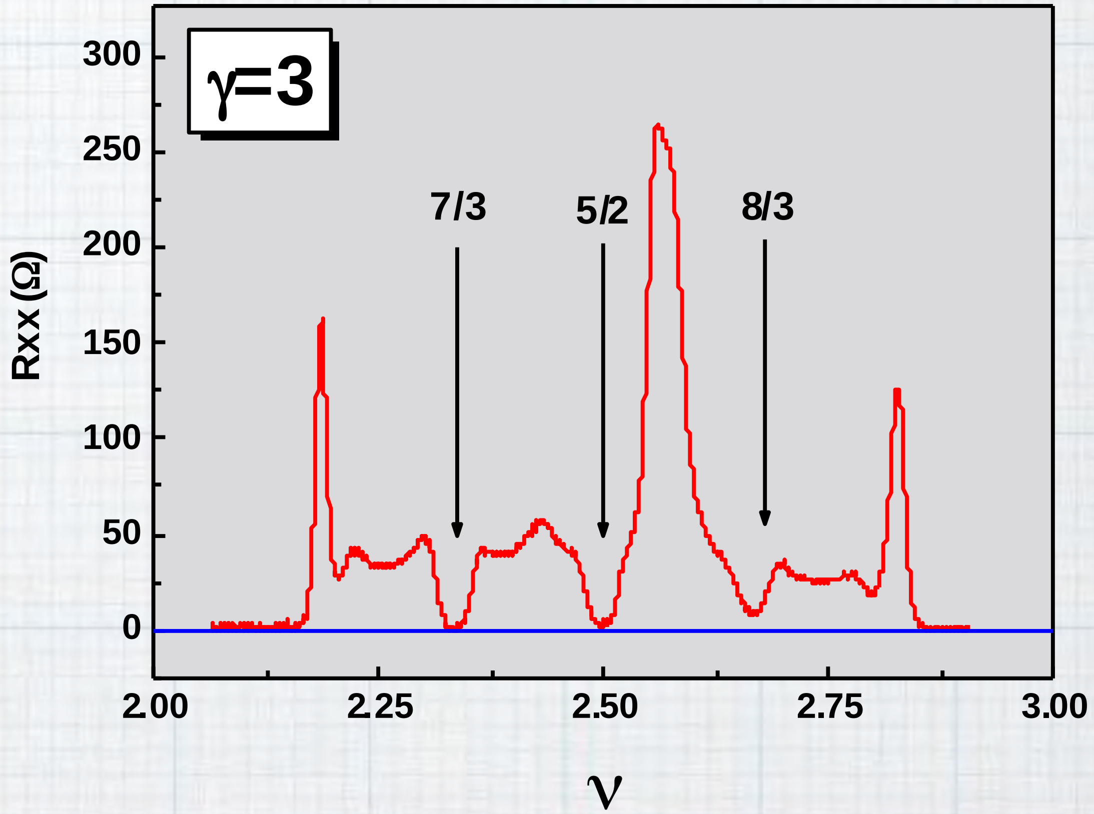
* ground state degeneracy (braiding is non-abelian)

shallow DX centers over doping

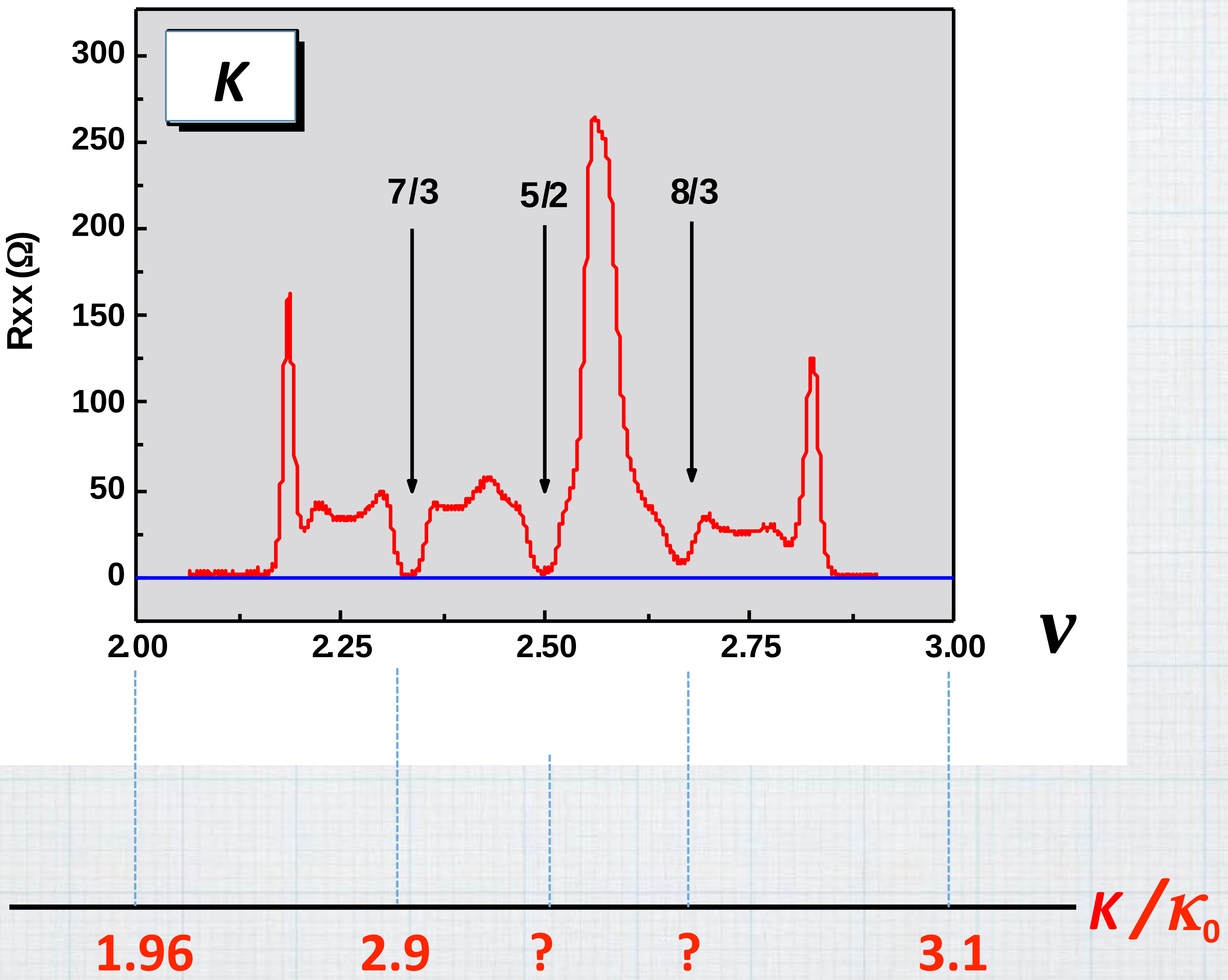
delta doping in $Al_xGa_{1-x}As$ (x=23÷25 %)





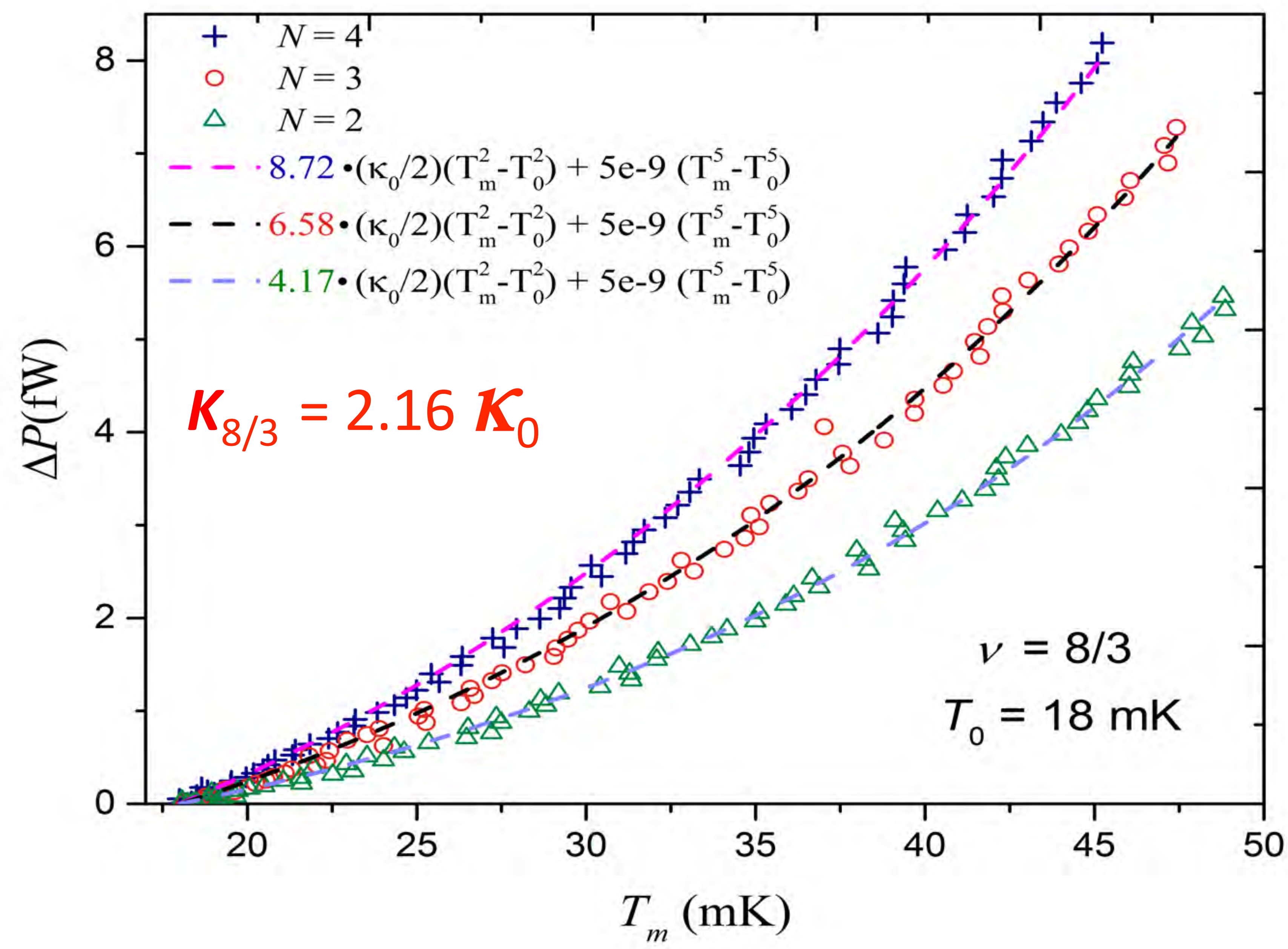


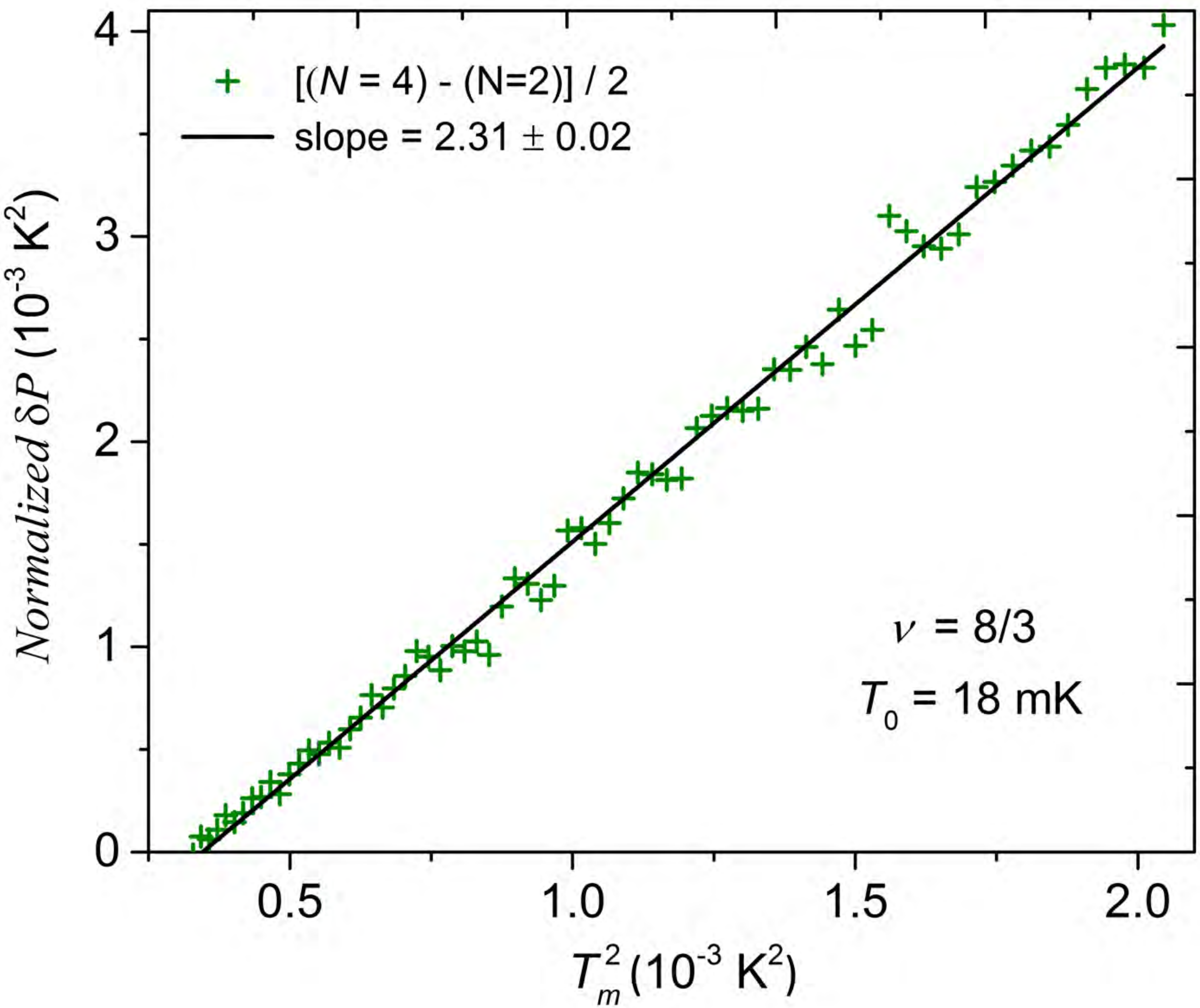
- NO illumination
- NO parallel conductance
- NO bulk thermal conductance
- stable gates (QPC replaced by continuous gate)
- low resistance floating reservoir

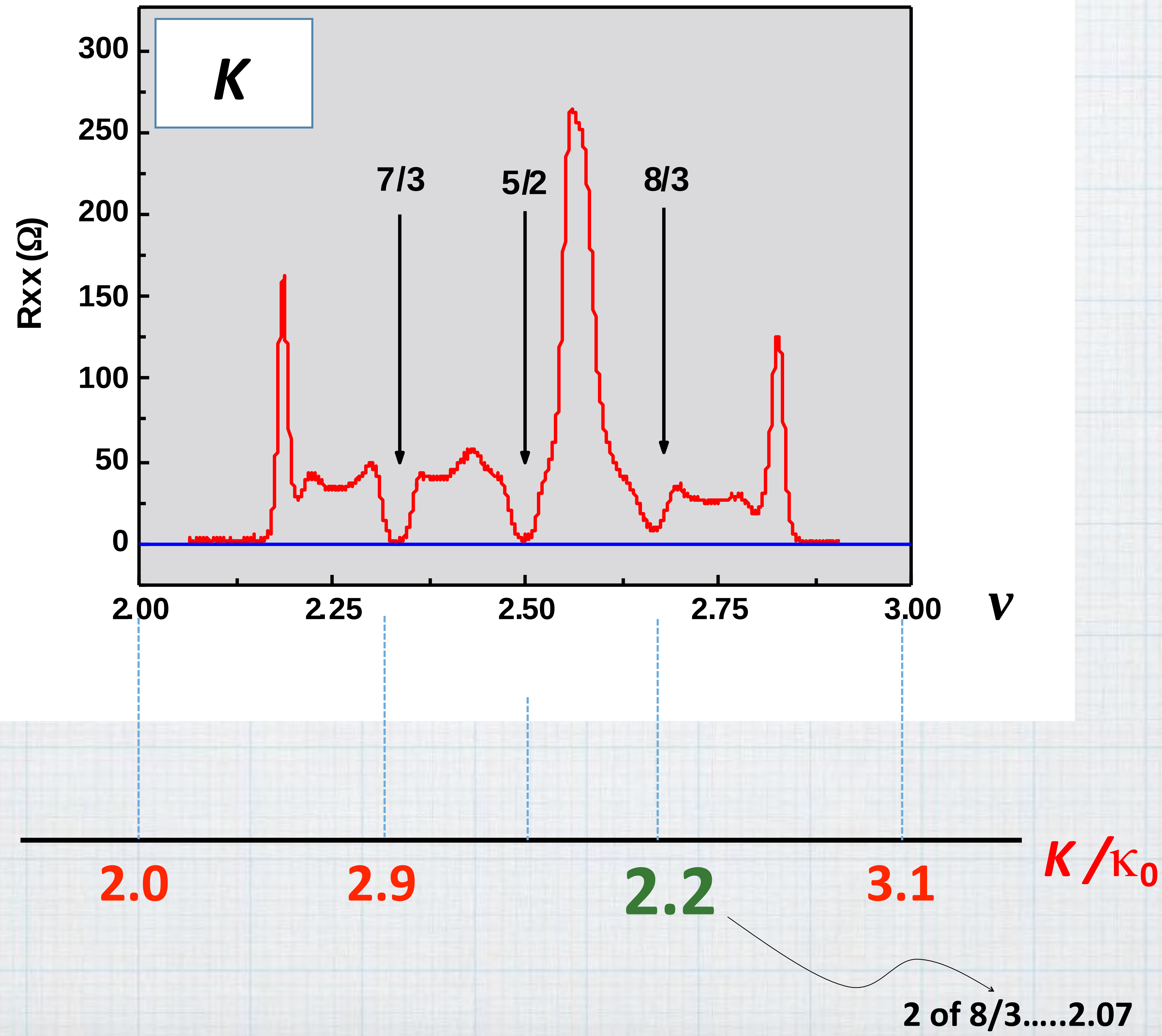


K
300
250
200
150
100
50
0
Rxx (Ω)
7/3
5/2
8/3
2.00
2.25
2.50
2.75
3.00
ν
κ/κ0
1.96
2.9
?
?
3.1

thermal conductance of ν =8/3 R_{xx}>0

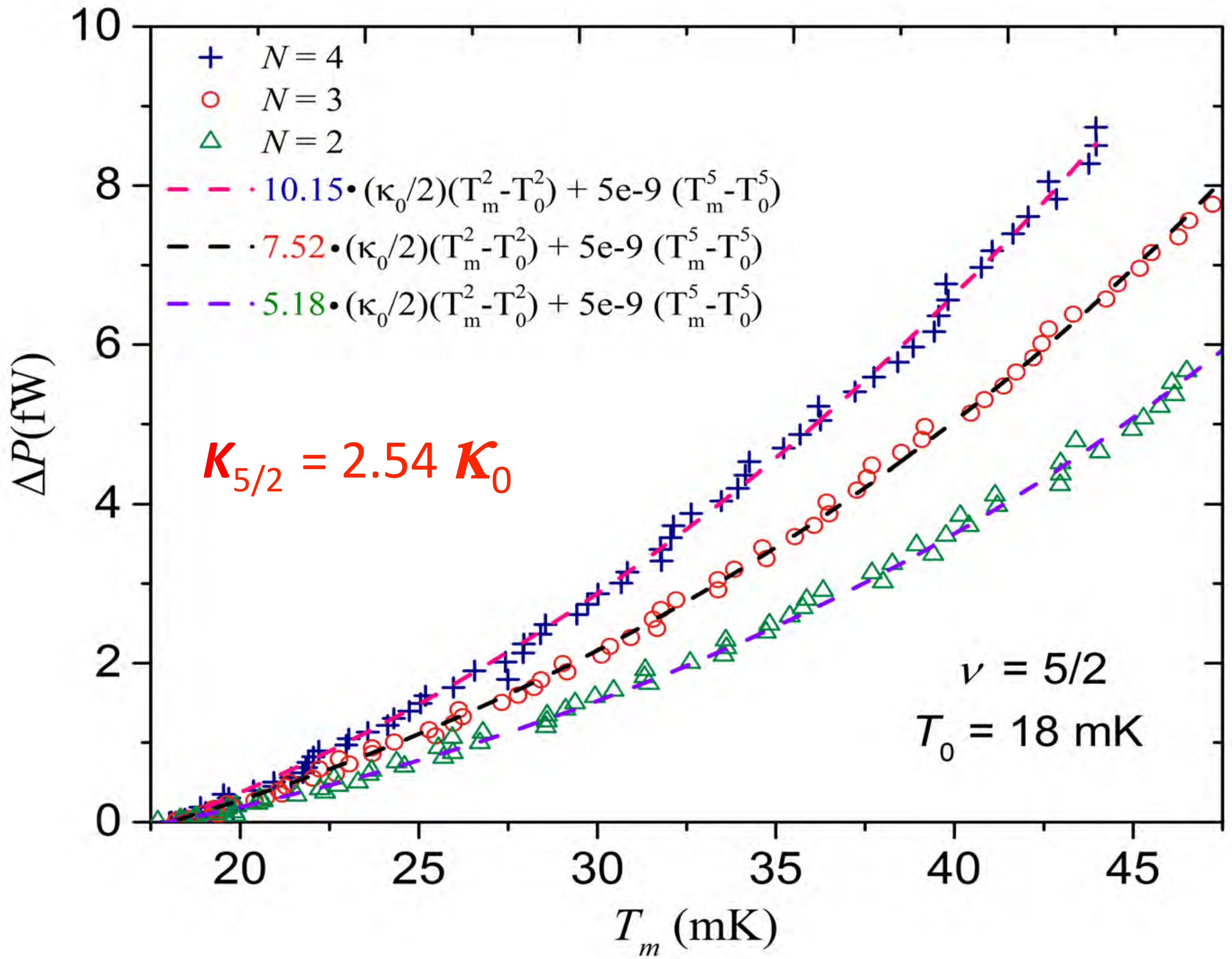



[(N = 4) - (N=2)] / 2
slope = 2.31 ± 0.02
ν = 8/3
T0 = 18 mK
Normalized δP (10^-3 K^2)
T_m^2 (10^-3 K^2)
0
1
2
3
4
0.5
1.0
1.5
2.0

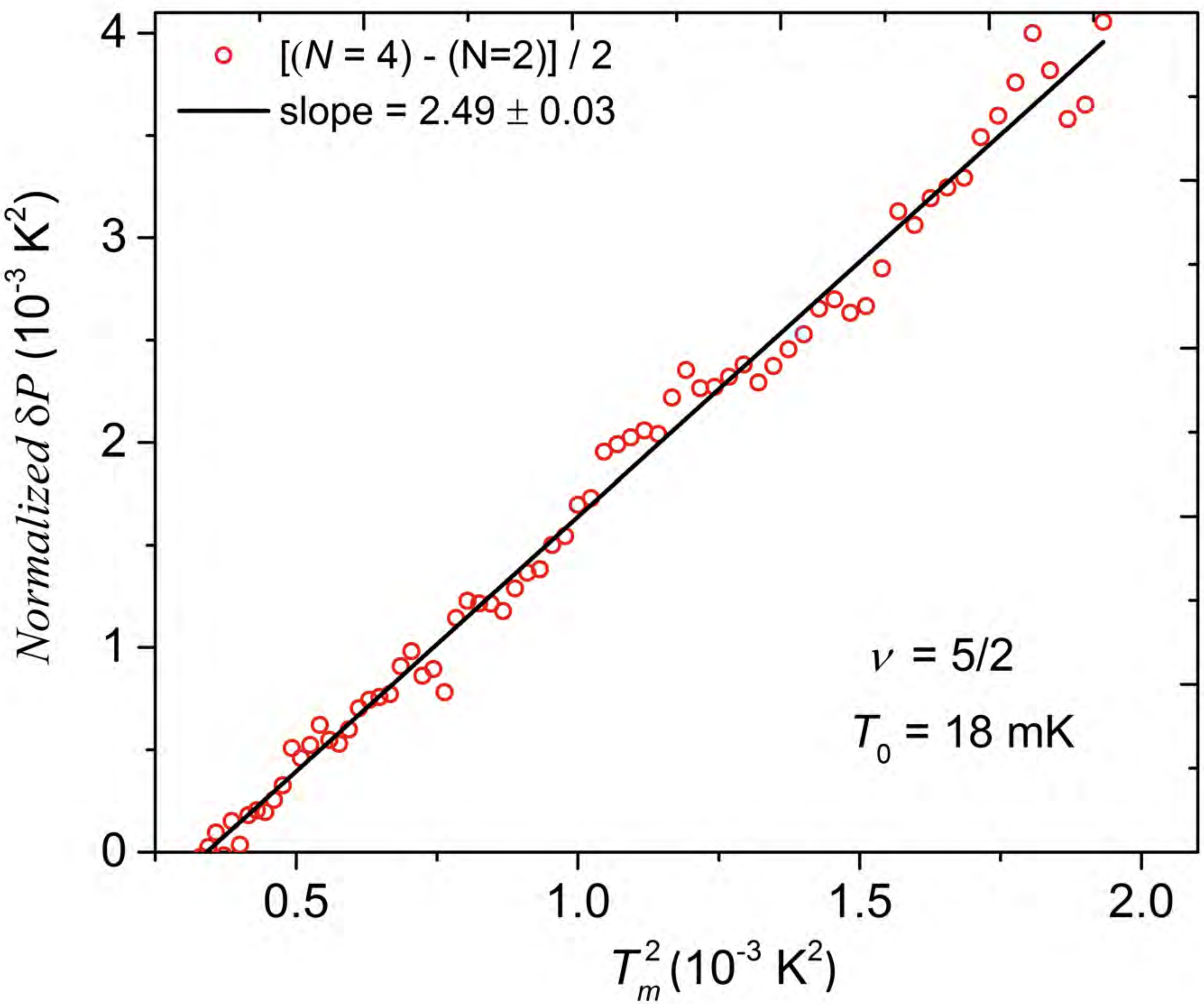


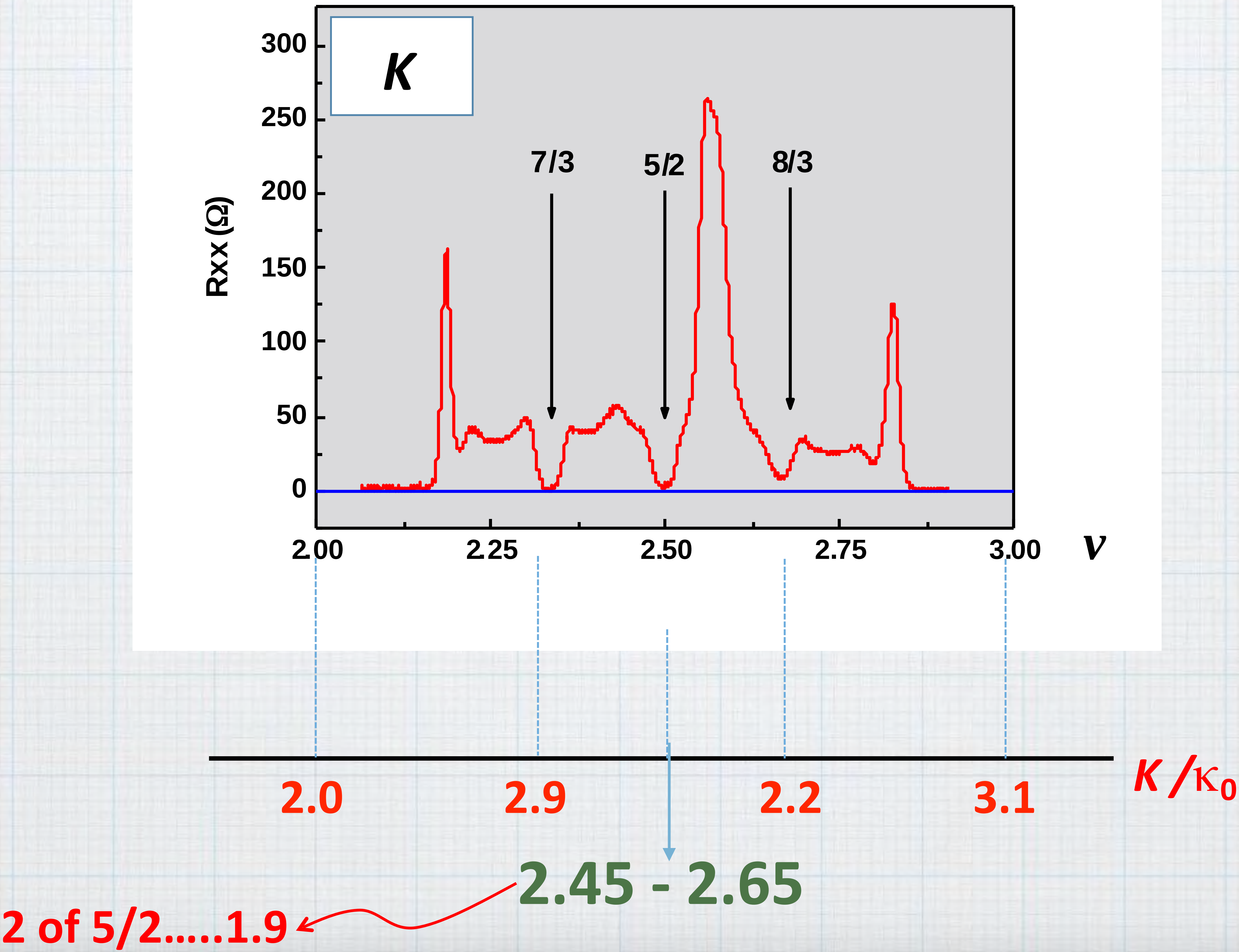
K
300
250
200
150
100
50
0
Rxx (Ω)
7/3
5/2
8/3
2.00
2.25
2.50
2.75
3.00
ν
2.0
2.9
2.2
3.1
K /κ0
2 of 8/3.....2.07

thermal conductance of *ν* =5/2

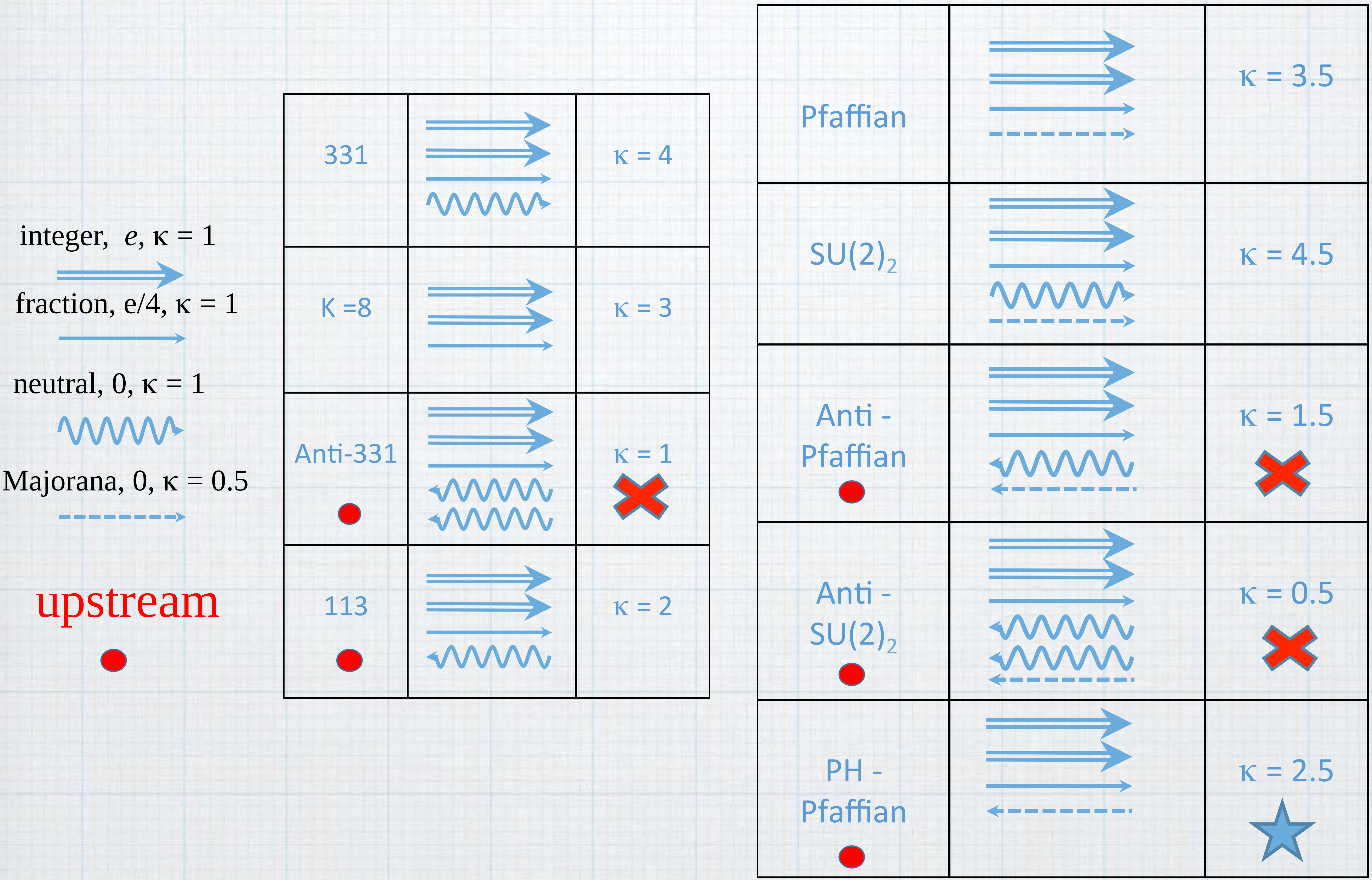


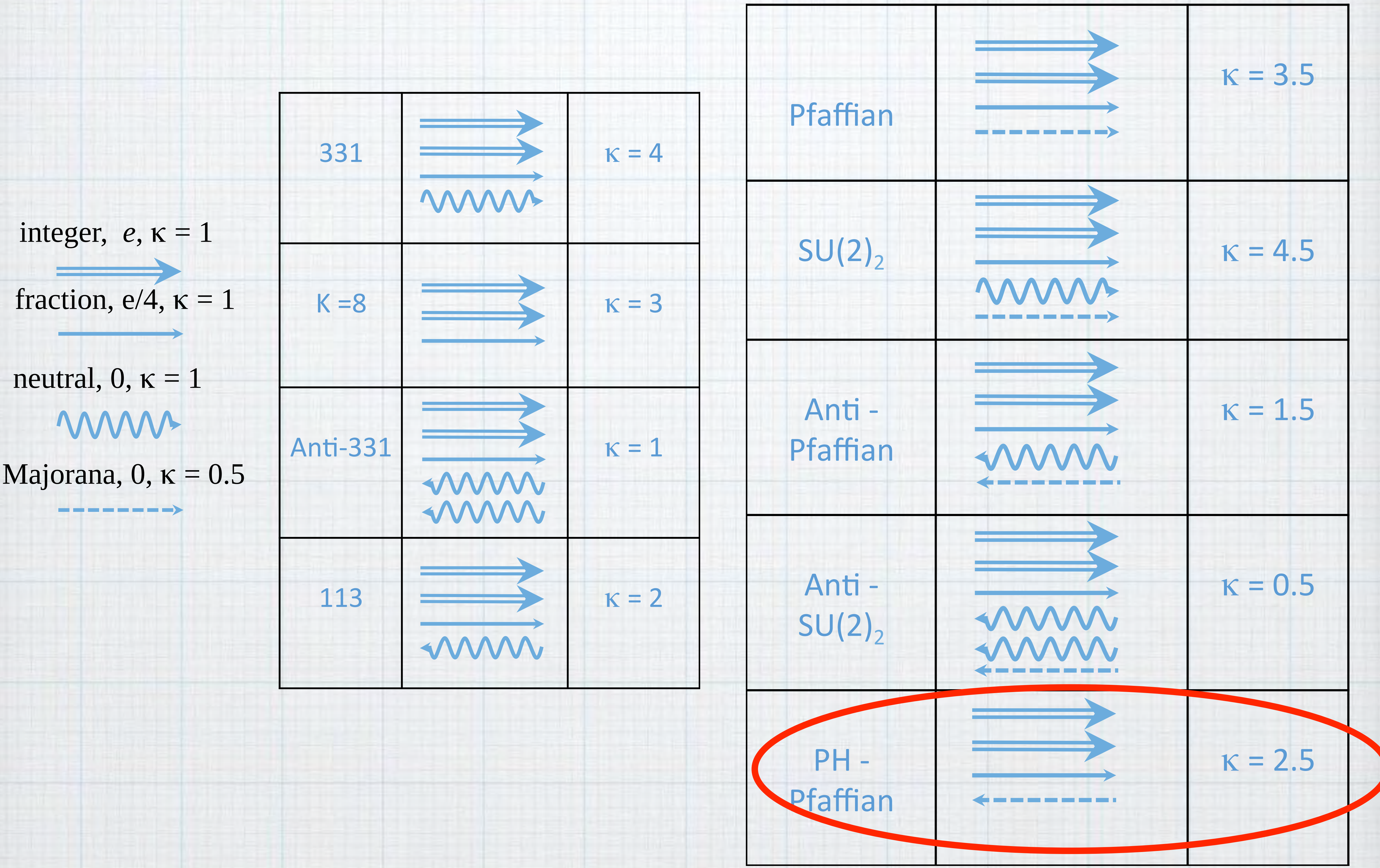
thermal conductance of ν =5/2





K
Rxx (Ω)
300
250
200
150
100
50
0
7/3
5/2
8/3
2.00
2.25
2.50
2.75
3.00
ν
2.0
2.9
2.2
3.1
K /κ0
2.45 - 2.65
2 of 5/2.....1.9

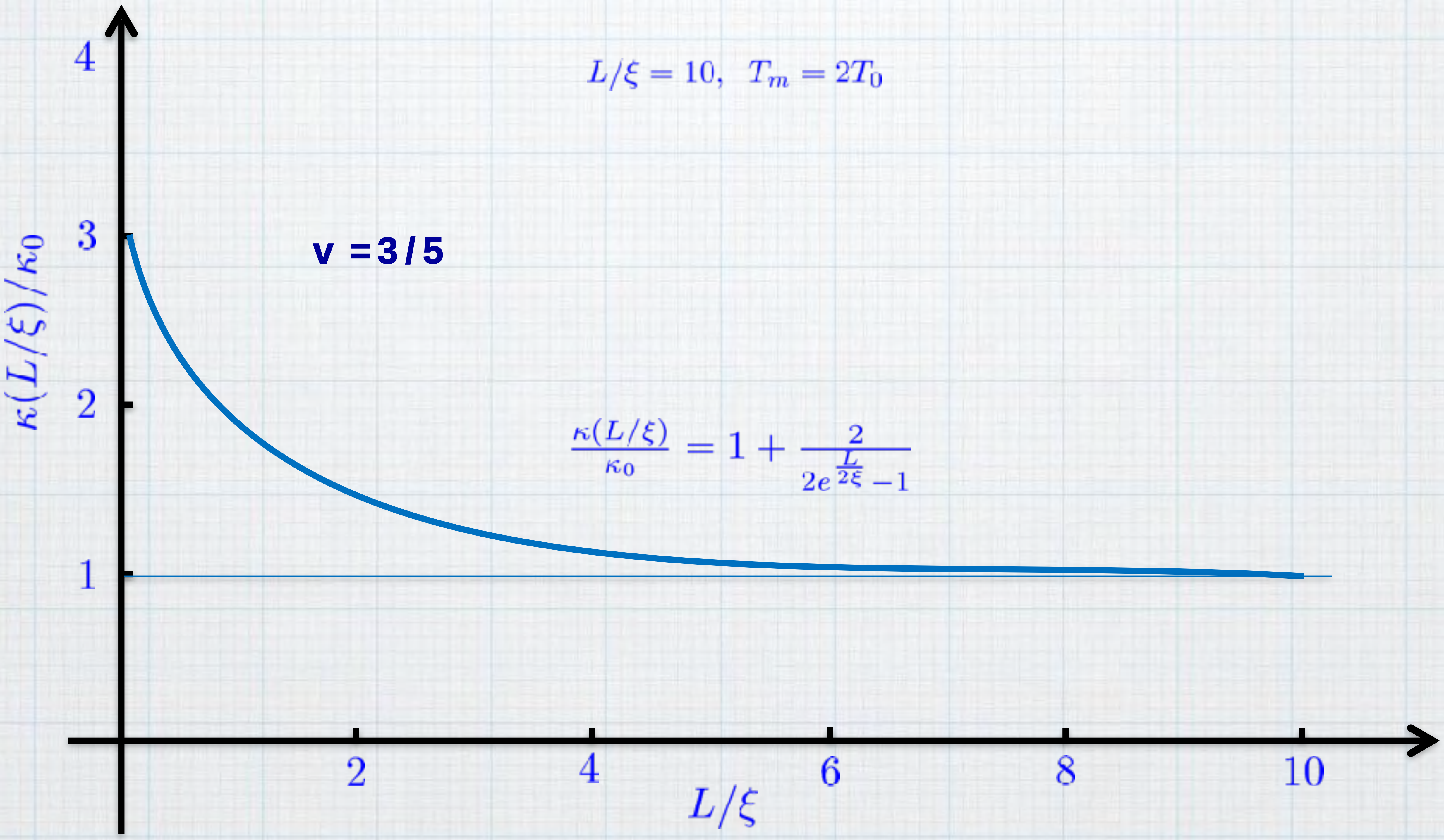

integer, e, κ = 1
fraction, e/4, κ = 1
neutral, 0, κ = 1
Majorana, 0, κ = 0.5
upstream
331
κ = 4
K =8
κ = 3
Anti-331
κ = 1
113
κ = 2
Pfaffian
κ = 3.5
SU(2)2
κ = 4.5
Anti - Pfaffian
κ = 1.5
Anti - SU(2)2
κ = 0.5
PH - Pfaffian
κ = 2.5



Son 2015, Feldman 2016

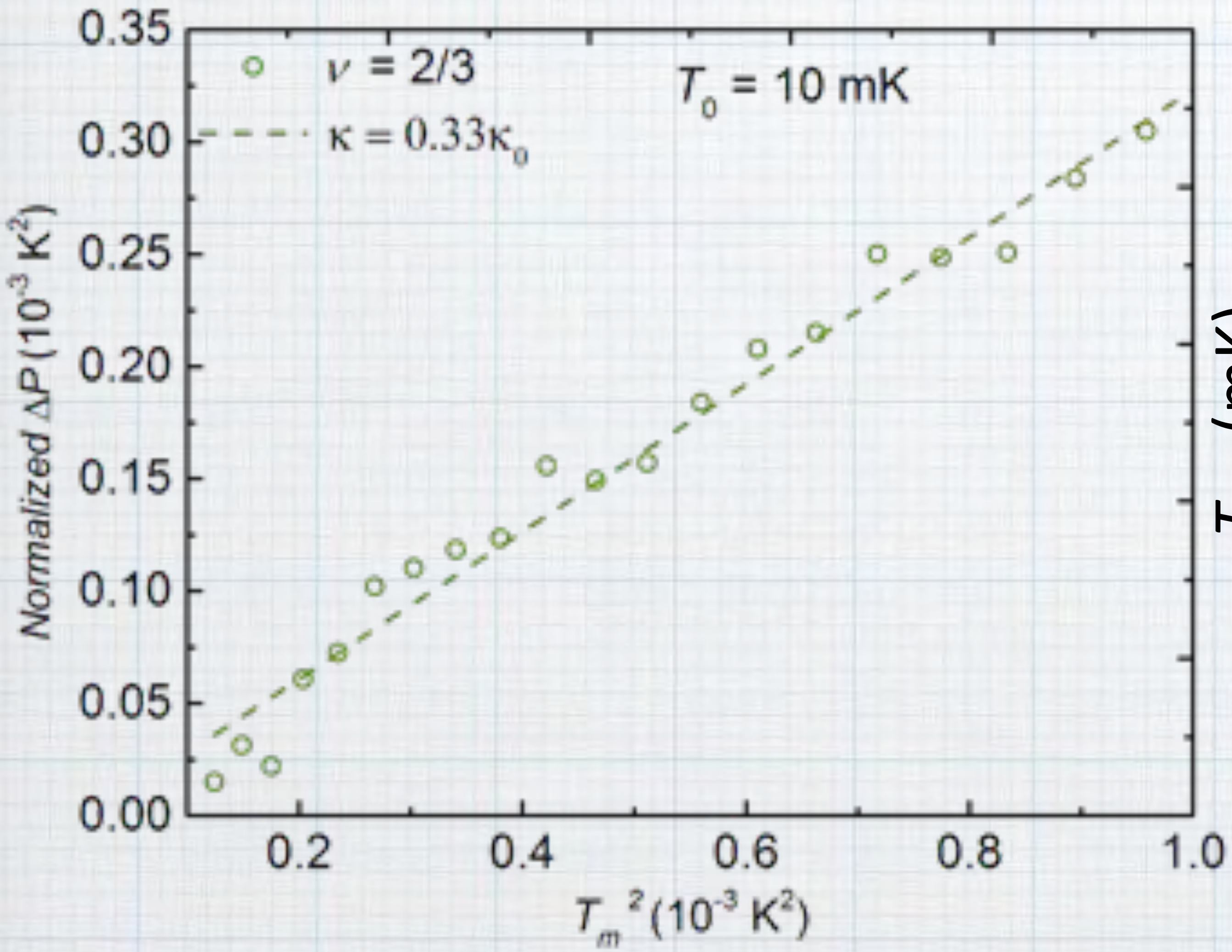
Majorana likely found!!!

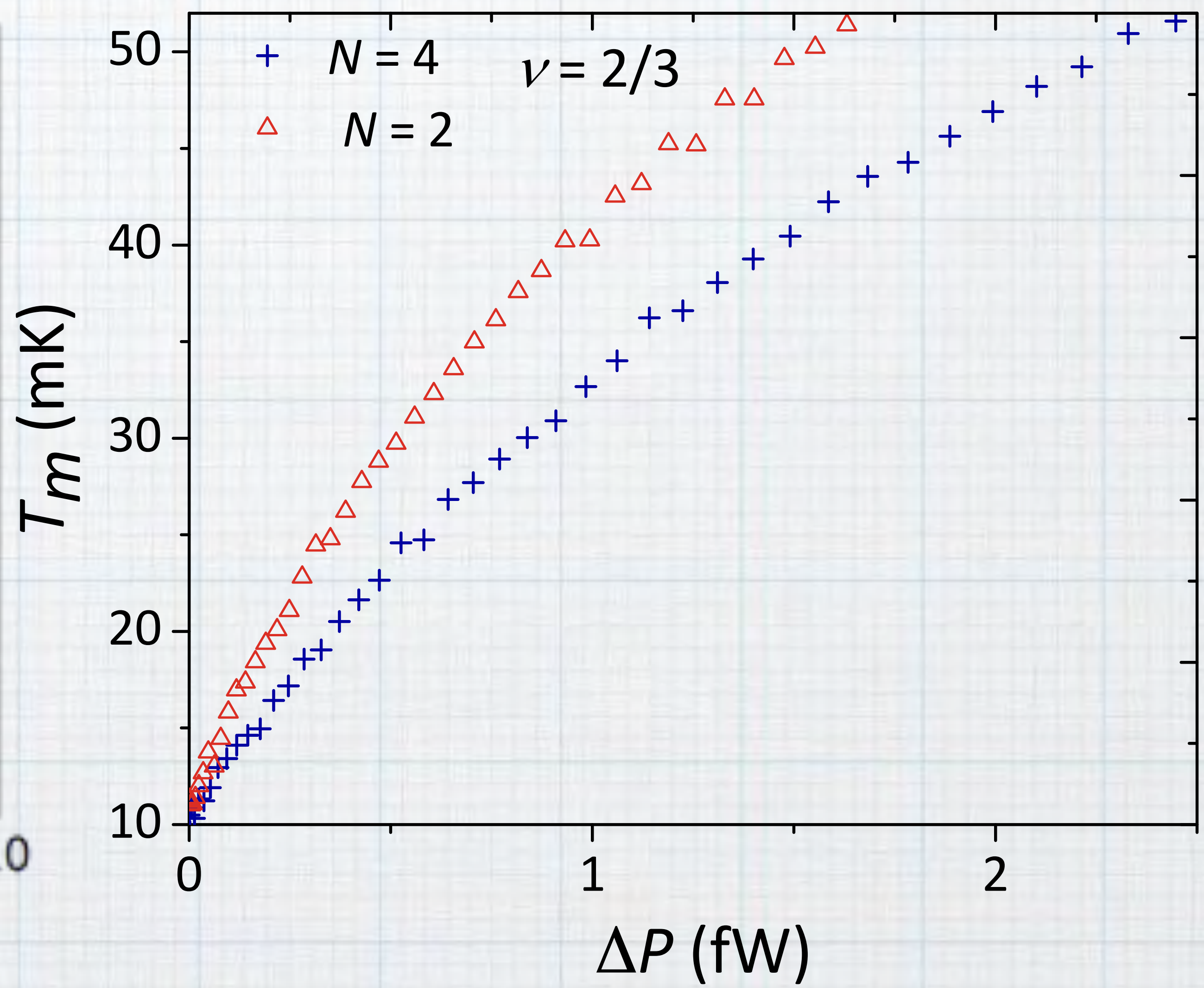
heat conductance w/length



ν = 2/3

$$J_e \simeq 0.33 \cdot 0.5\kappa_0 (T_m^2 - T_0^2) \quad T_0 = 10mK$$

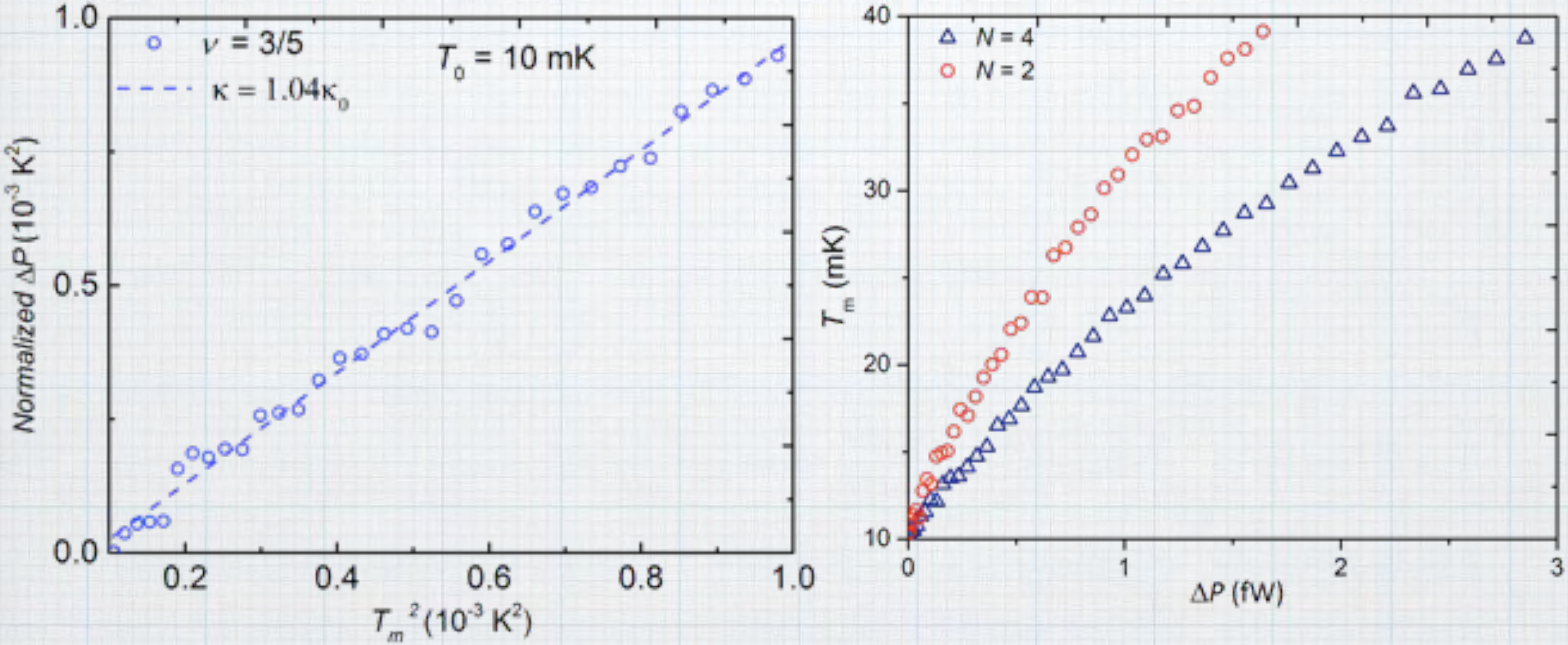




κ > 0…..symmetric up and down of arms, hence…. actual **κ /2**

ν = 3/5

$$J_e \simeq 1.04 \cdot 0.5\kappa_0 (T_m^2 - T_0^2) \quad T_0 = 10mK$$



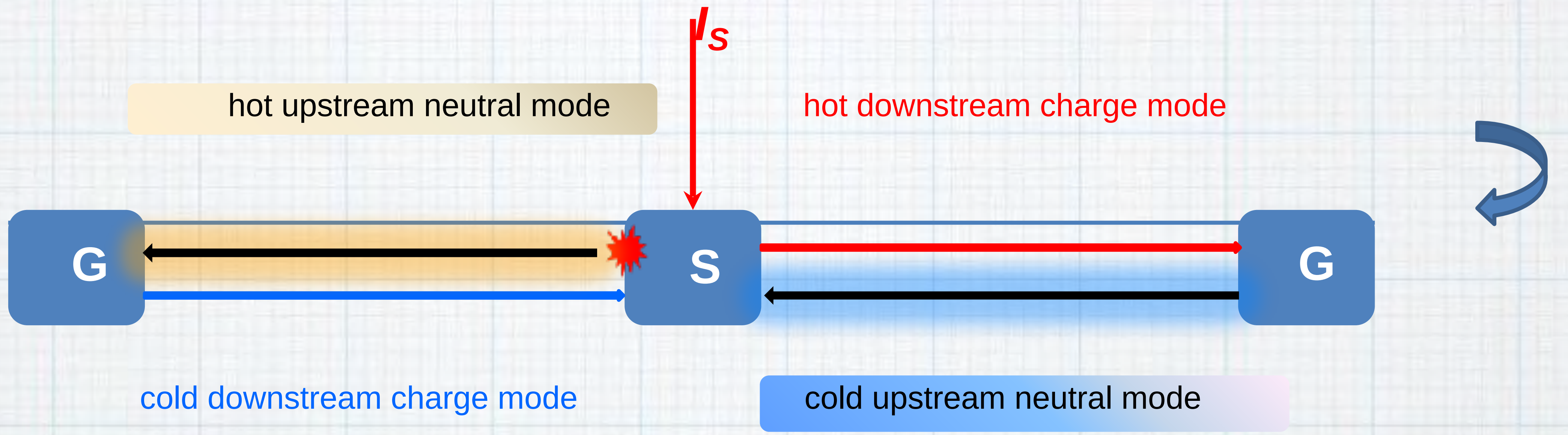
$\nu = 2/3$

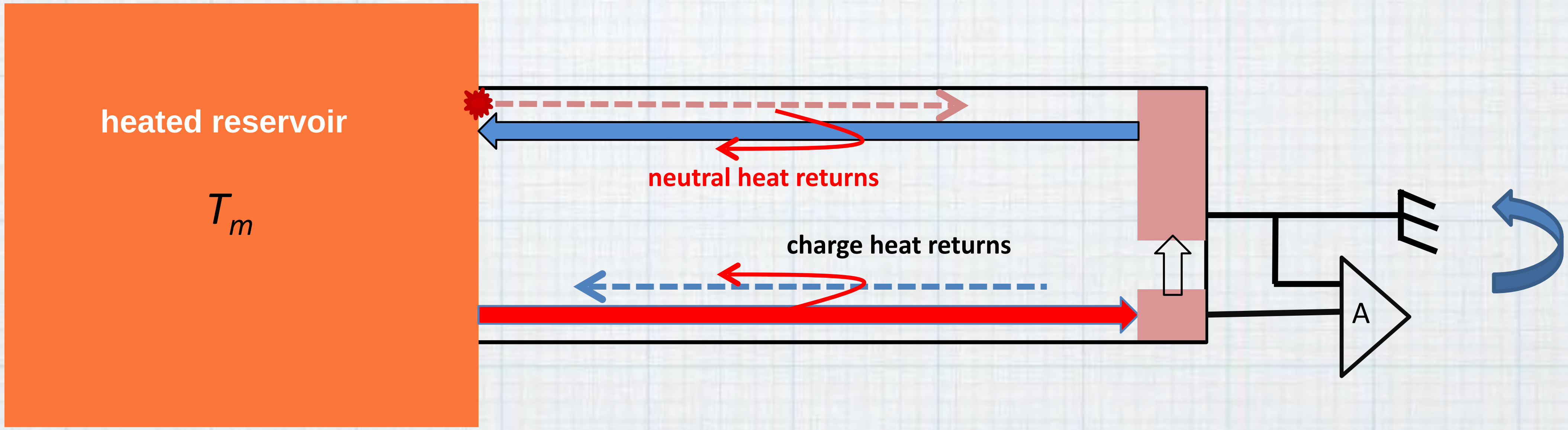
$$\frac{K}{\kappa_0} = \frac{2}{1 + \frac{L}{\xi_T}} \qquad L \sim 150 \mu m$$

$$J_e \simeq 0.33 \cdot 0.5\kappa_0 (T_m^2 - T_0^2) \quad T_m^{ava} = 20mK \quad \Rightarrow \xi_T = 30\mu m$$

$$J_e \simeq 0.25 \cdot 0.5\kappa_0 (T_m^2 - T_0^2) \quad T_m^{ava} = 45mK \quad \Rightarrow \xi_T = 20\mu m$$

example......ν =2/3......why K=0 ?



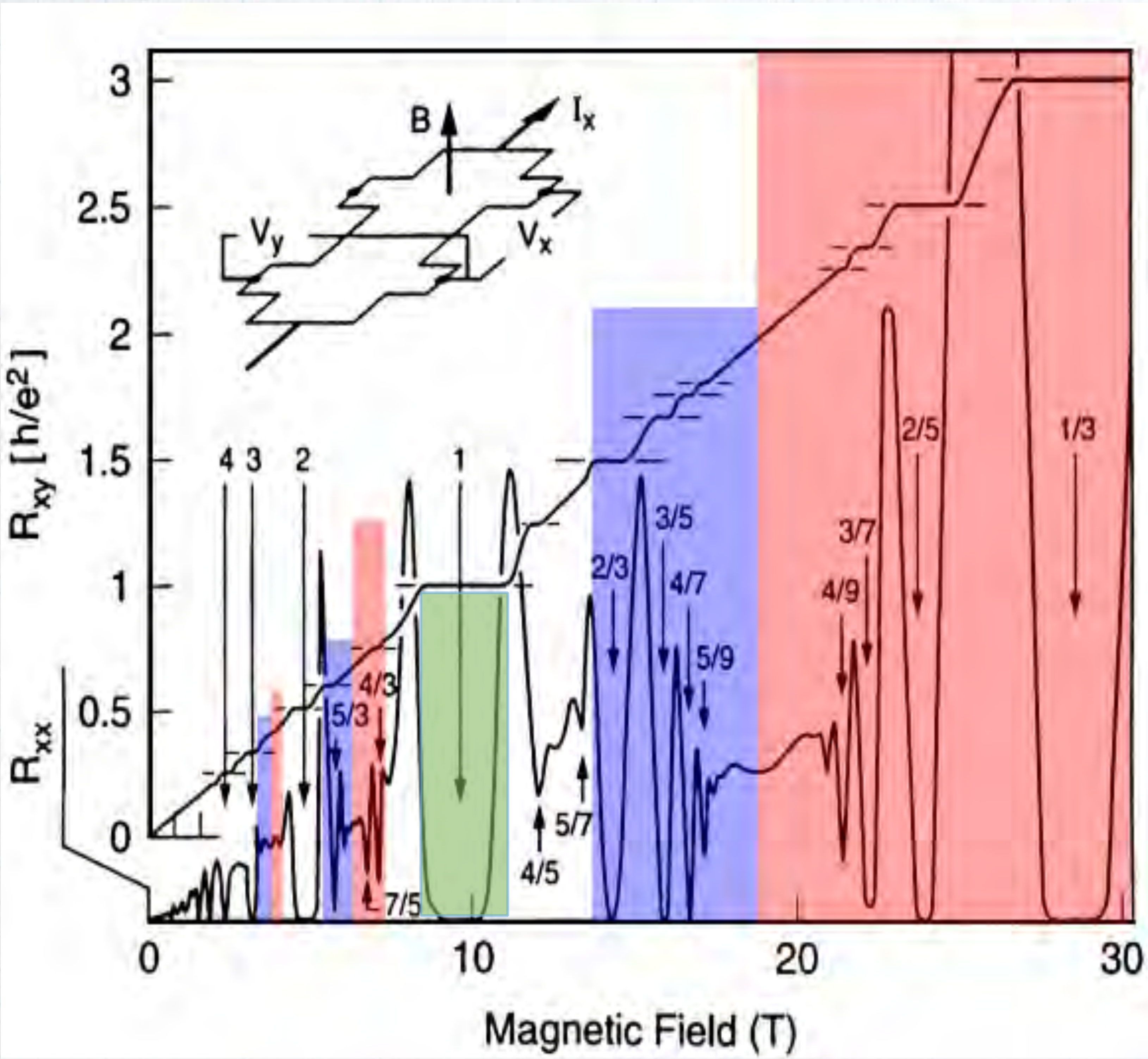


heat diffuses

thermal conductivity *vs* thermal conductance

length dependence thermal conductance

observation of upstream neutral edge modes



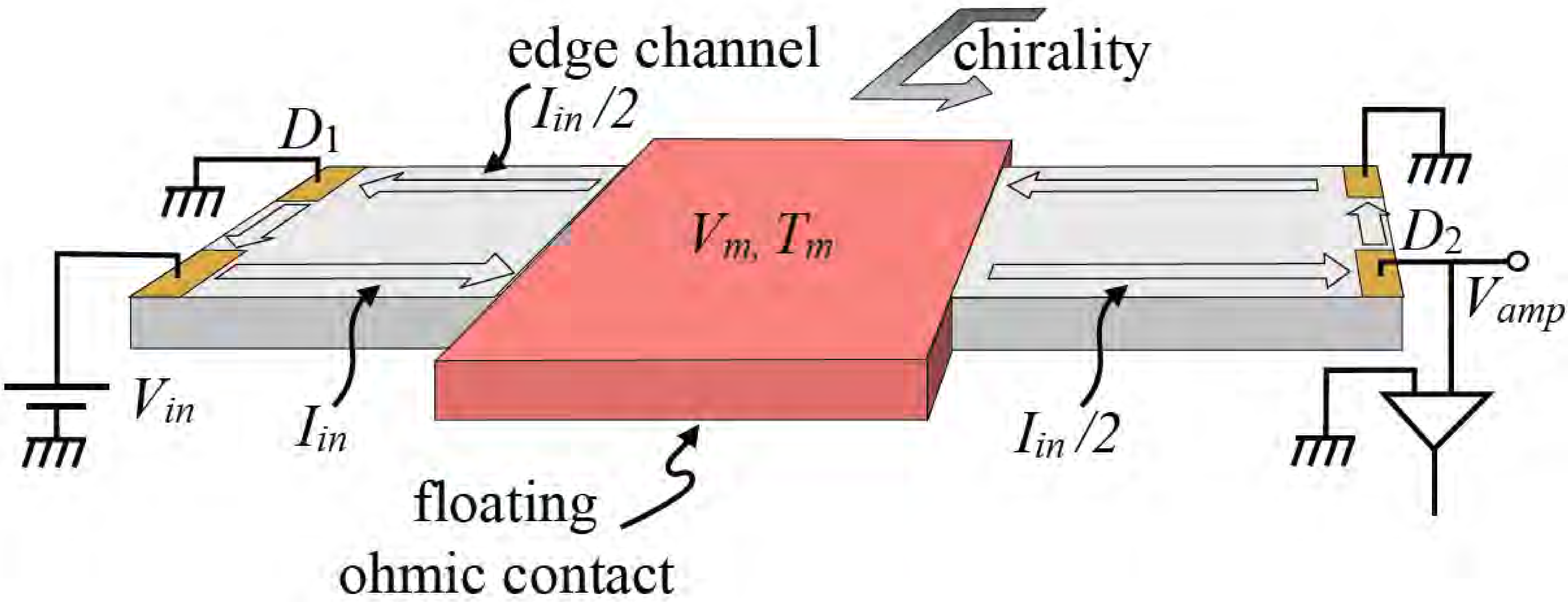
<u>shot noise</u>
ν = 2/3, 3/5, 1+2/3, 2+2/3 & 5/2
Bid, Nature (2010), Dolev, PRL (2011)

<u>QD thermometry</u>
ν = 2/3 edge at *ν* = 1 + bulk heat transport
Venkatachalam, Nature Physics (2012)

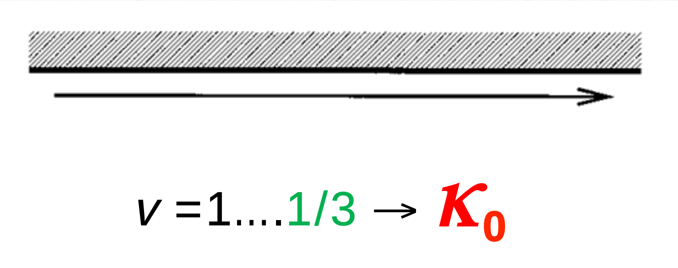
<u>QD thermoelectric current</u>
ν = 2/3
Gurman, Nature Comm. (2012)

<u>QD thermometry</u>
ν = 1+1/3 + bulk heat transport
Altimiras, PRL (2012)

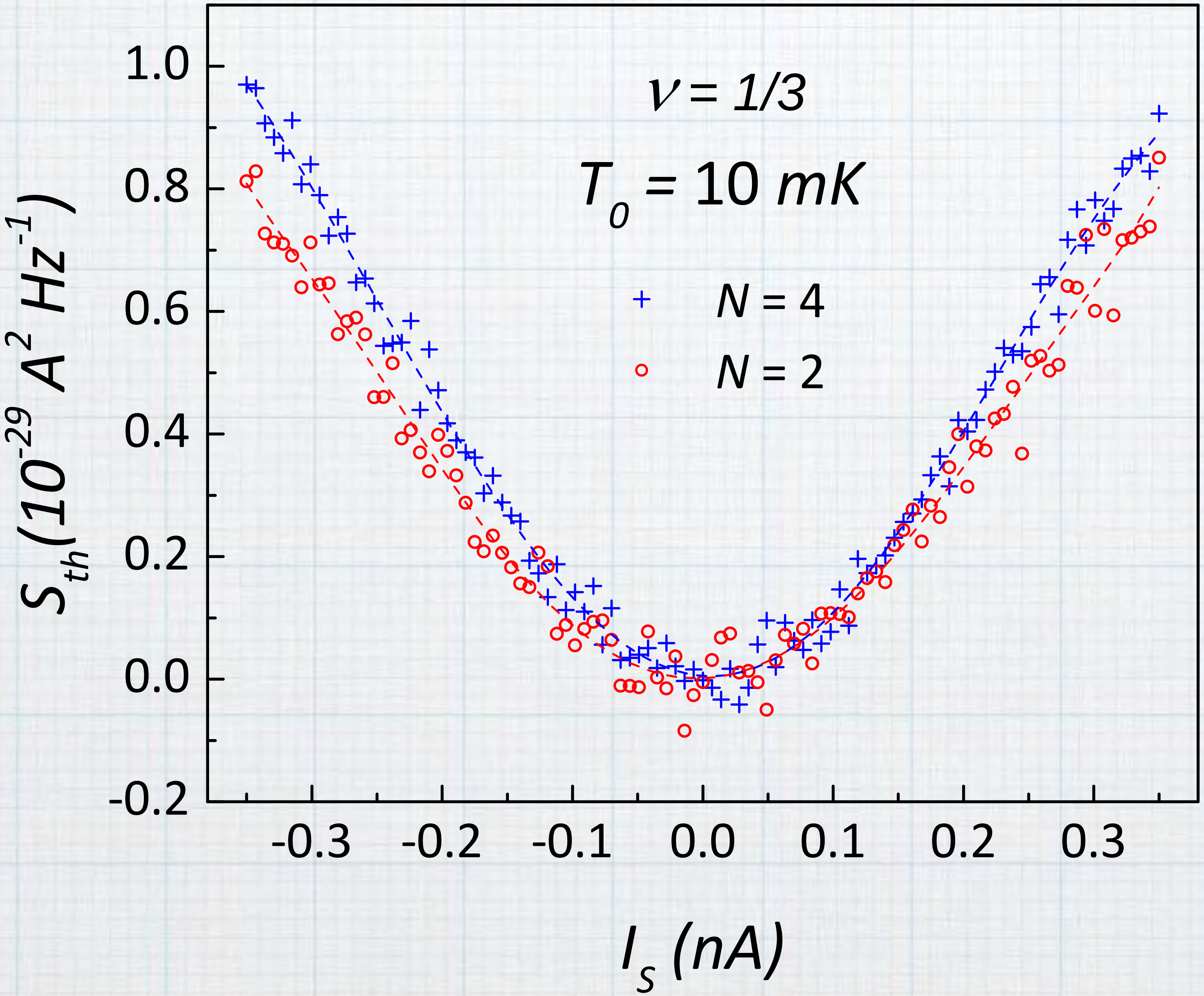
two–arm device



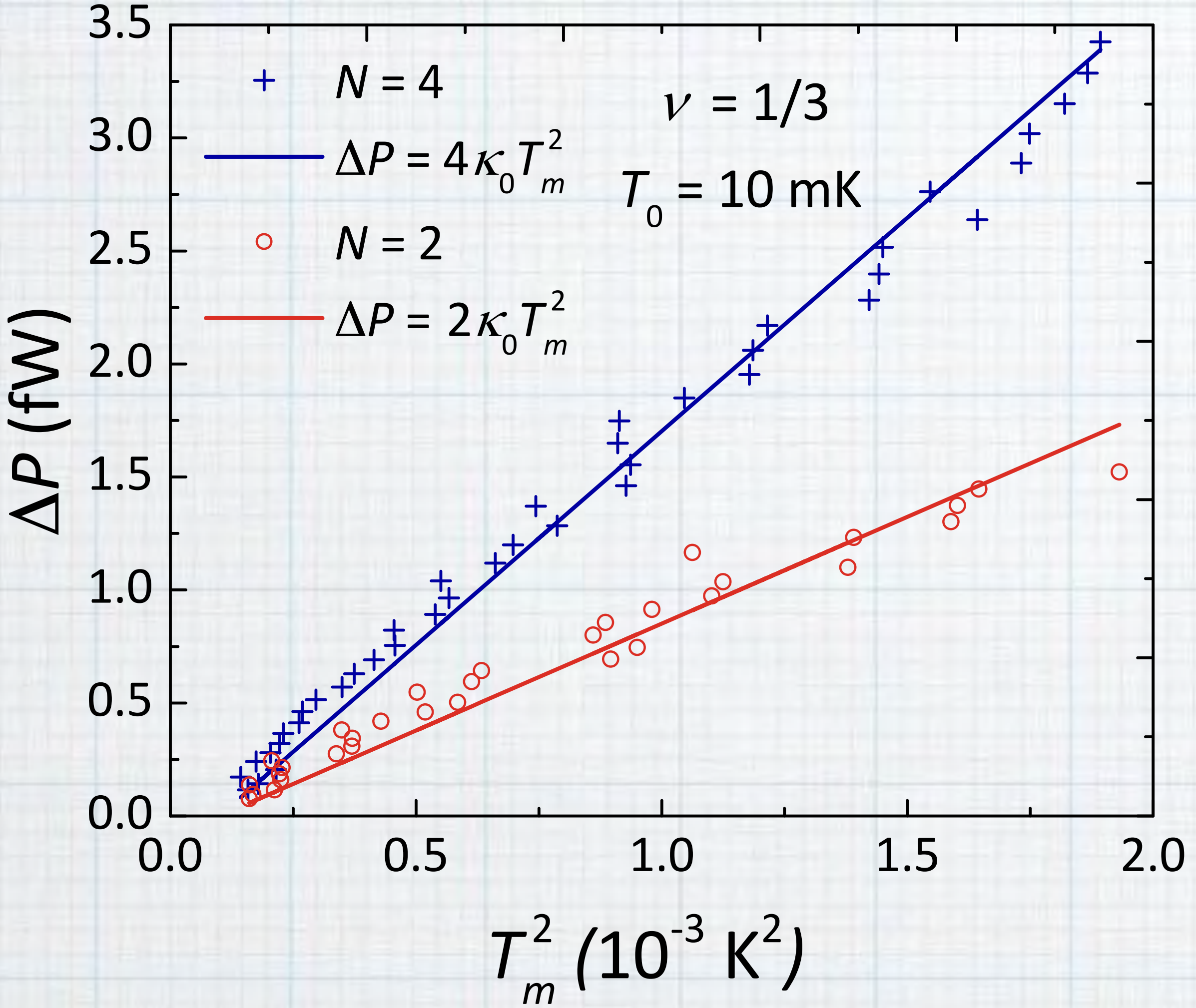
Results :



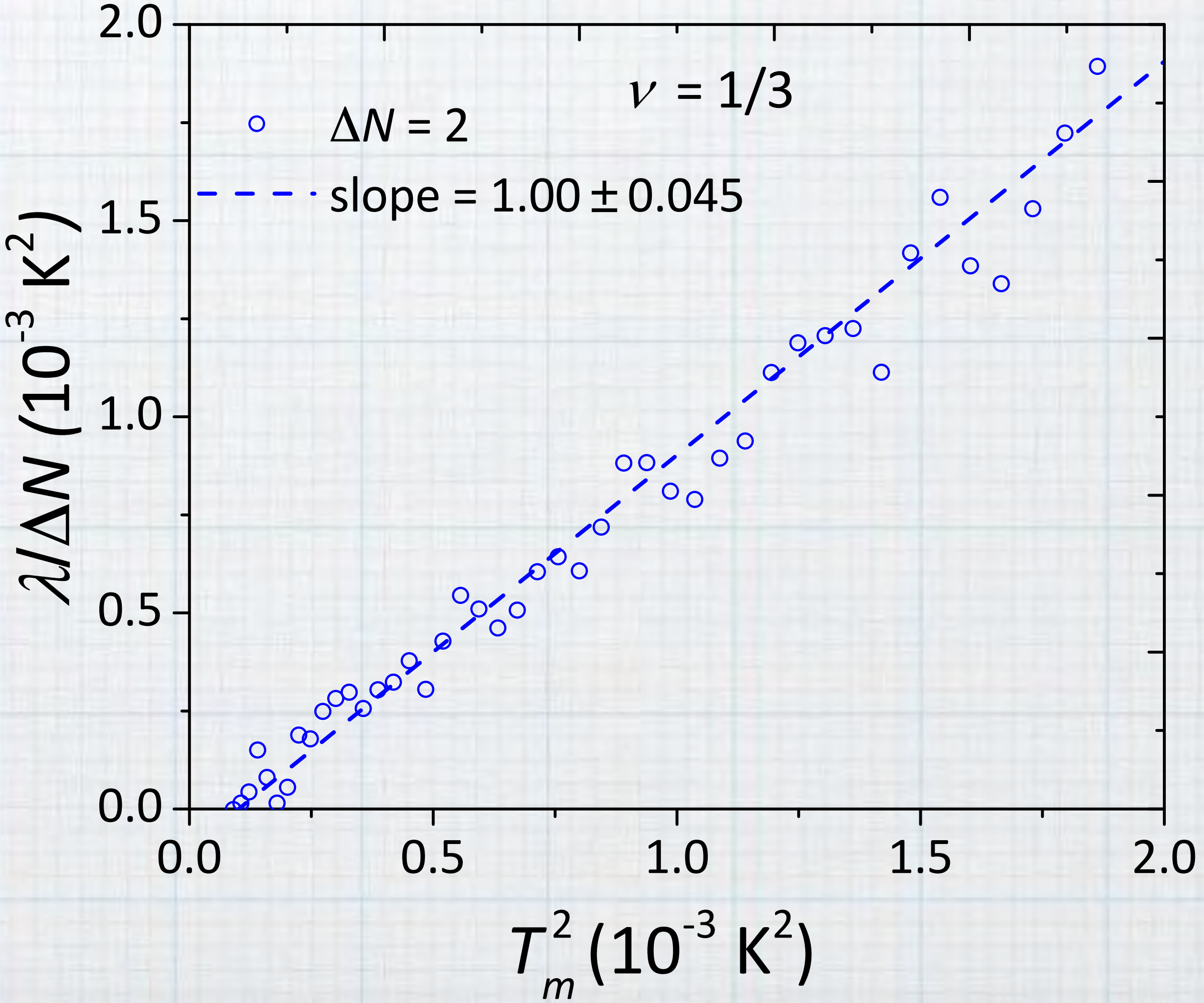
1 electron mode….**1** composite fermion mode



Results :



N = 4
ΔP = 4κ0Tm2
N = 2
ΔP = 2κ0Tm2
ν = 1/3
T0 = 10 mK
ΔP (fW)
Tm2 (10-3 K2)



ΔN = 2
slope = 1.00 ± 0.045
ν = 1/3
λ/ΔN (10-3 K2)
Tm2 (10-3 K2)

What sets the limit on heat flow

$E.t \approx \hbar$ sets a lower bound to the energy flow

In steady state, $\dot{E} = \frac{\pi k_B^2}{12\hbar} T^2$ & $\dot{S} = \frac{\pi k_B^2}{6\hbar} T$

Expression relating single channel entropy and energy flow is

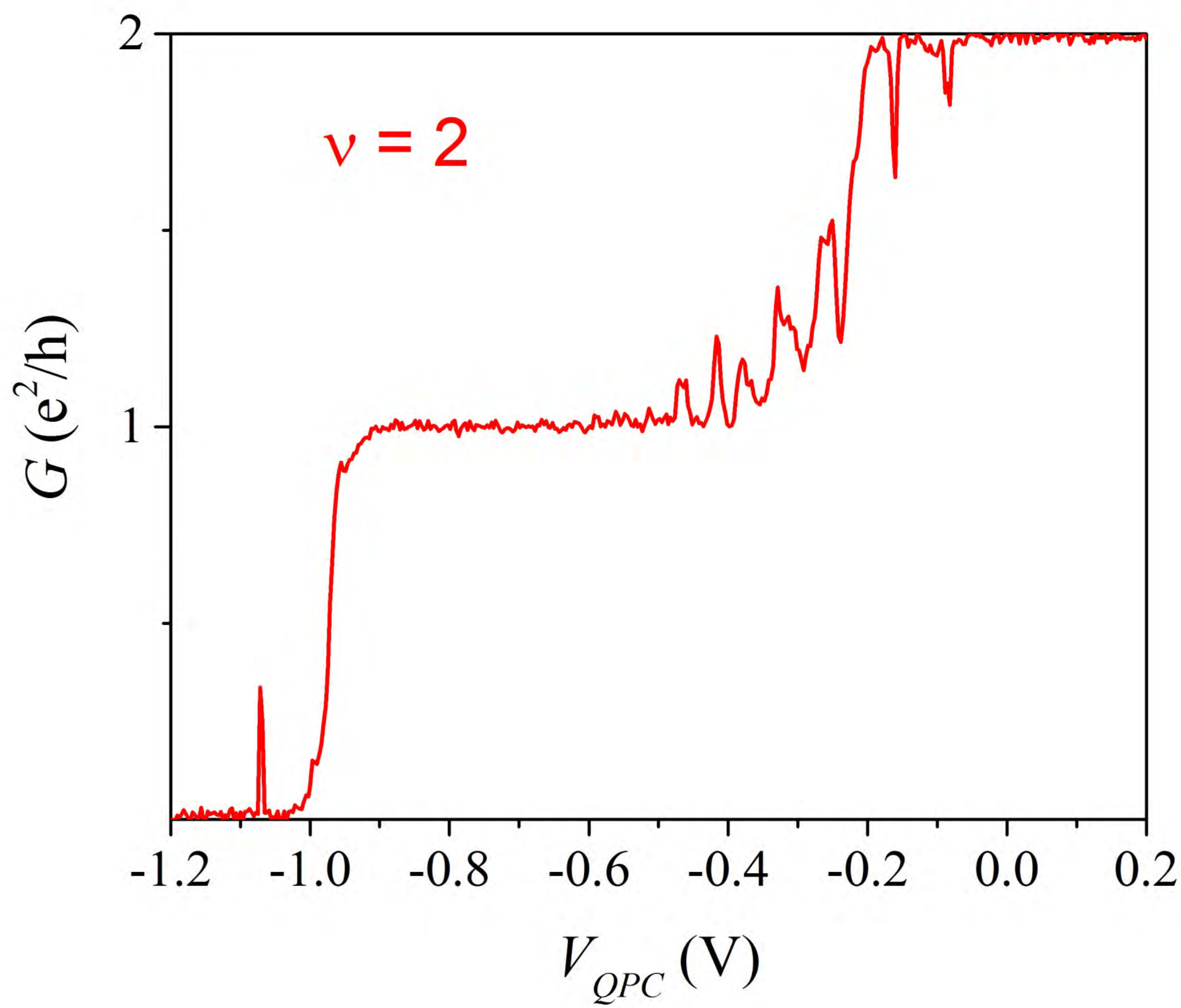
$$\dot{S}^2 \leq \frac{\pi k_B^2}{3\hbar} \dot{E}$$

using, $\dot{Q} = \dot{E}$ & $\frac{\dot{Q}}{T} \leq \dot{S}$

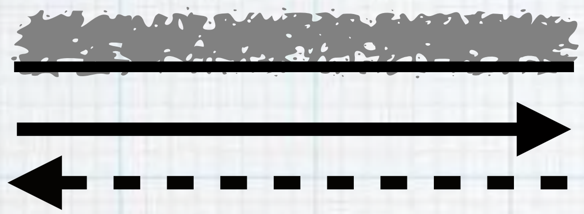
$$\dot{Q} \leq \frac{\pi k_B^2}{3\hbar} T^2 \quad \text{or} \quad J \leq \frac{\pi^2 k_B^2}{6h} T^2$$

J. B. Pendry, J. Phys. A (1983)

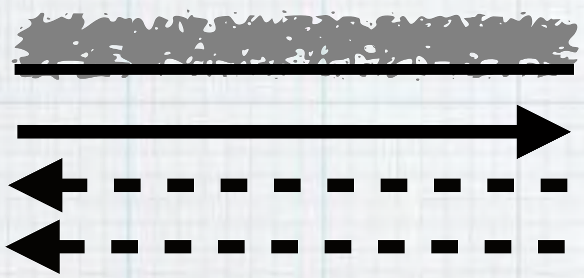
Rego and Kirzenow, PRB (1999)


ν = 2
2
1
G (e²/h)
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
V_QPC (V)

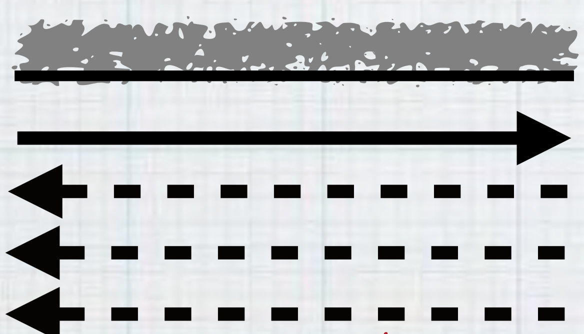
hole-like states :



$$\nu = \frac{2}{3} \quad \kappa = 0$$



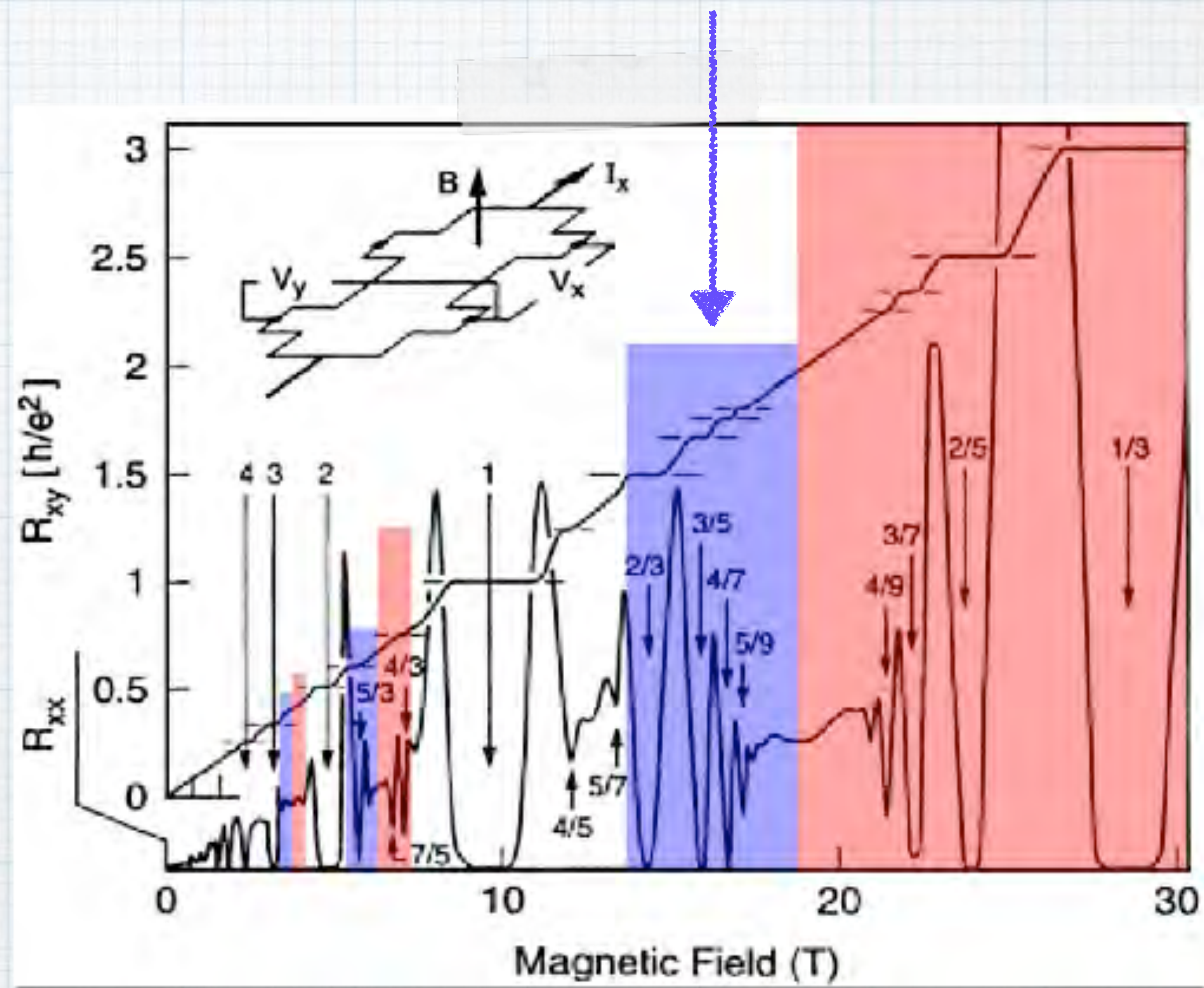
$$\nu = \frac{3}{5} \quad \kappa = -\kappa_0$$



$$\nu = \frac{4}{7} \quad \kappa = -2\kappa_0$$

hole-like states

more interesting states



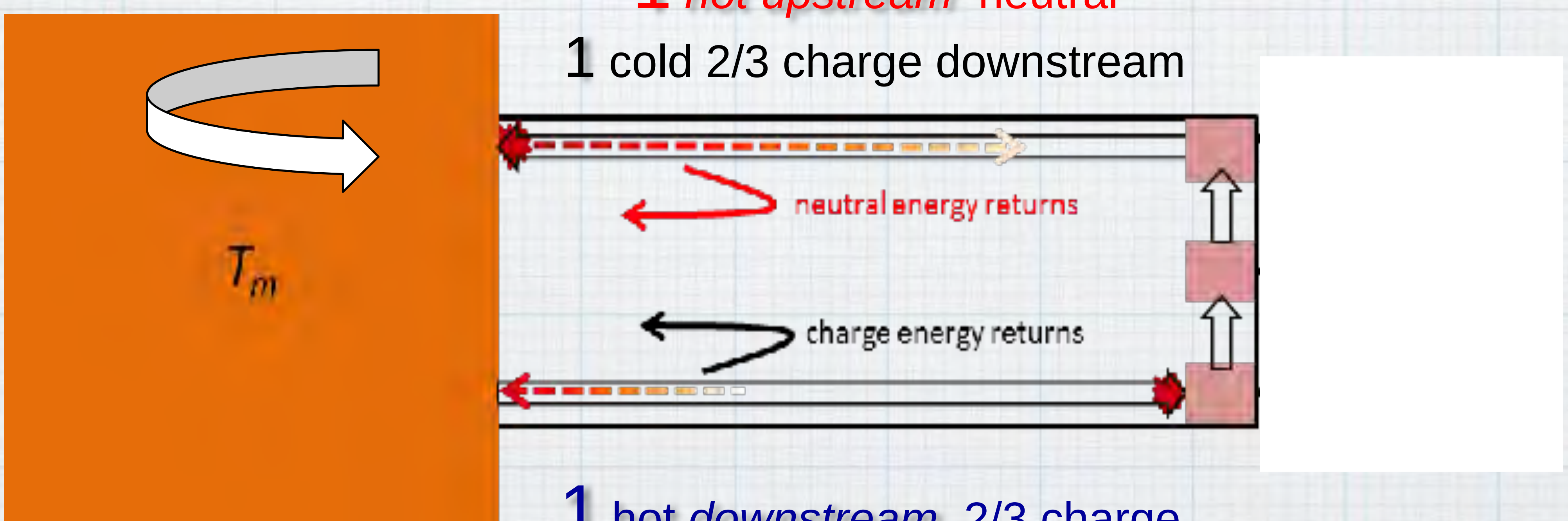
hole-like states + neutral modes.....ν =2/3

expected …… κ =0 all electrical heat returns

distance~150μm, T_0~10mK

1 *hot upstream* neutral

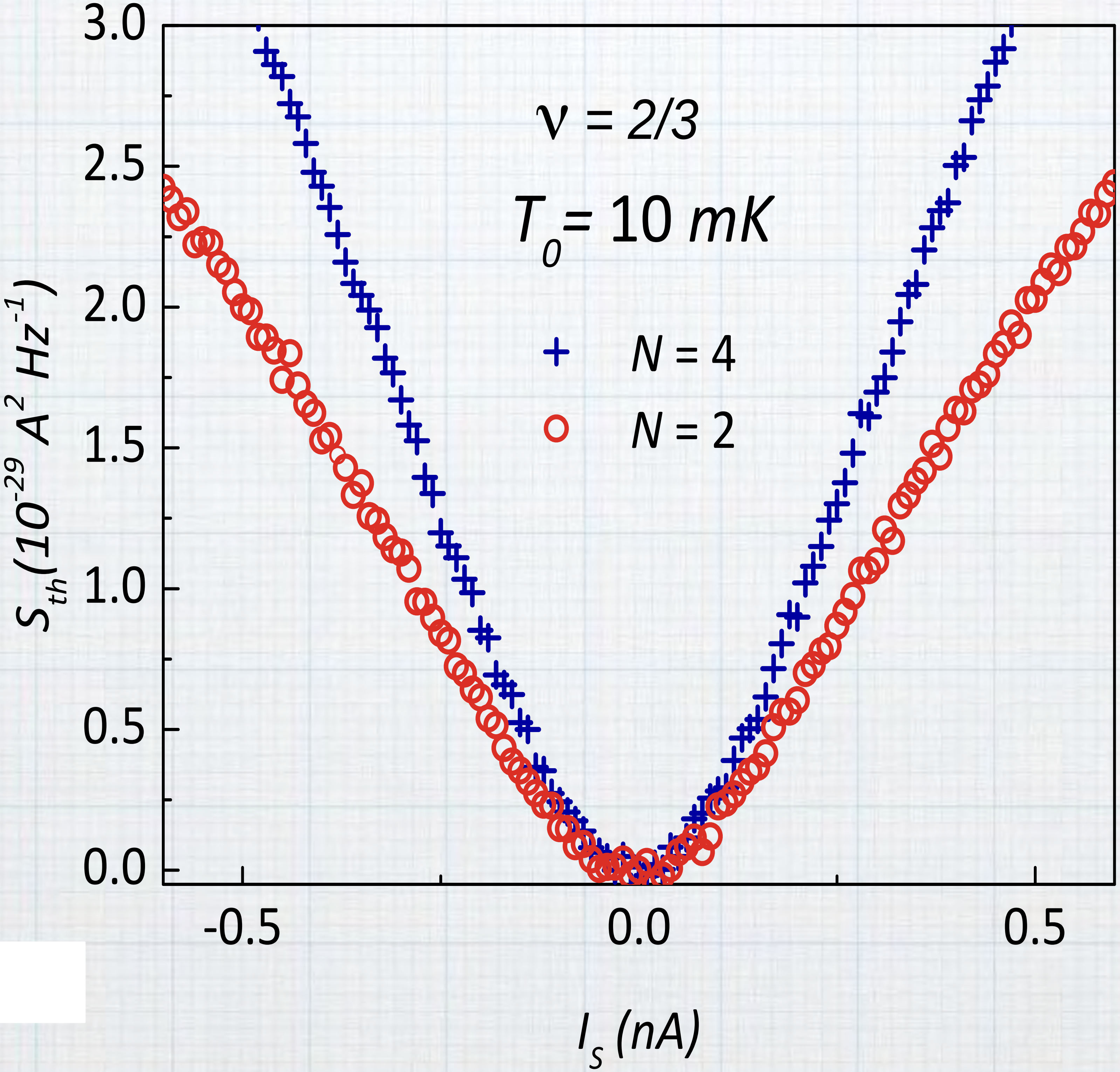
1 cold 2/3 charge downstream



1 hot *downstream* 2/3 charge

1 cold neutral upstream

thermal noise – spectral density



Generalization....

G.C Rego and G Kirczenow
Fractional exclusion statistics and the universal thermal conductance: A unifying approach
Phys. Rev. B **59,** 13080-13086 (1999)

$$J_q = \frac{q}{h}\int_\varepsilon d\varepsilon\left(\eta_R - \eta_L\right)\text{........electric current}$$

$$J_{th} = \frac{1}{h}\int_\varepsilon d\varepsilon \cdot \varepsilon\left(\eta_R - \eta_L\right)\text{.....heat current}$$

$$\eta_g = \frac{1}{Z(x,g)+g} \qquad x = \frac{\varepsilon - \mu}{k_B T}$$

$g = 0$ bosonic
$g = 1$ fermionic
$g = 3$ $\nu = 1/3$

$$G_q = \frac{1}{g}\cdot\frac{e}{h}\cdot e \text{ ....} g \text{ dependent}$$

$$G_{th} = 1\cdot\frac{\pi^2 k_B^2}{3h}\cdot T\text{............} g \text{ independent}$$